Author: Sun, Z.
Title: Going global to local: achieving agri-food sustainability from a spatially explicit input-output analysis perspective
Issue Date: 2021-06-01

References

7 References

1. Wiedmann, T. & Lenzen, M. Environmental and social footprints of international trade. *Nature Geoscience* vol. 11 314–321 (2018).

2. Moran, D., Giljum, S., Kanemoto, K. & Godar, J. From Satellite to Supply Chain: New Approaches Connect Earth Observation to Economic Decisions. *One Earth* **3**, 5–8 (2020).

3. Wood, S. A., Smith, M. R., Fanzo, J., Remans, R. & Defries, R. S. Trade and the equitability of global food nutrient distribution. *Nat. Sustain.* **1**, 34–37 (2018).

4. Kummu, M. *et al.* Interplay of trade and food system resilience: Gains on supply diversity over time at the cost of trade independency. *Glob. Food Sec.* **24**, 100360 (2020).

5. D'Odorico, P. *et al.* The Global Food-Energy-Water Nexus. *Reviews of Geophysics* vol. 56 456–531 (2018).

6. D'Odorico, P., Carr, J. A., Laio, F., Ridolfi, L. & Vandoni, S. Feeding humanity through global food trade. *Earth's Futur.* **2**, 458–469 (2014).

7. Janssens, C. *et al.* Global hunger and climate change adaptation through international trade. *Nat. Clim. Chang.* **10**, 829–835 (2020).

8. Seekell, D. *et al.* Resilience in the global food system. *Environ. Res. Lett.* **12**, 025010 (2017).

9. Li, Y. L., Chen, B. & Chen, G. Q. Carbon network embodied in international trade: Global structural evolution and its policy implications. *Energy Policy* **139**, 111316 (2020).

10. Kastner, T., Erb, K. H. & Haberl, H. Rapid growth in agricultural trade: Effects on global area efficiency and the role of management. *Environ. Res. Lett.* **9**, 034015 (2014).

11. Qiang, W. *et al.* Trends in global virtual land trade in relation to agricultural products. *Land use policy* **92**, 104439 (2020).

12. Marques, A. *et al.* Increasing impacts of land use on biodiversity and carbon sequestration driven by population and economic growth. *Nat. Ecol. Evol.* **3**, 628–637 (2019).

13. Wang, R., Hertwich, E. & Zimmerman, J. B. Virtual water flows uphill toward money. *Environ. Sci. Technol.* **50**, 12320–12330 (2016).

14. Wiedmann, T., Lenzen, M., Keyßer, L. T. & Steinberger, J. K. Scientists' warning on affluence. *Nat. Commun.* **11**, 1–10 (2020).

15. UNEP. Decoupling Natural Resource Use and Environmental Impacts from Economic Growth. (2011).

16. Kanemoto, K. & Moran, D. Carbon-Footprint Accounting for the Next Phase of Globalization: Status and Opportunities. *One Earth* **1**, 35–38 (2019).

17. Fuchs, R., Brown, C. & Rounsevell, M. Europe's Green Deal offshores environmental damage to other nations. *Nature* vol. 586 671–673 (2020).

18. Scheelbeek, P. F. D. *et al.* United Kingdom's fruit and vegetable supply is increasingly dependent on imports from climate-vulnerable producing countries. *Nat. Food* **1**, 705–712 (2020).

19. Pendrill, F. *et al.* Agricultural and forestry trade drives large share of tropical deforestation emissions. *Glob. Environ. Chang.* **56**, 1–10 (2019).

20. Tukker, A., Pollitt, H. & Henkemans, M. Consumption-based carbon accounting: sense and sensibility. *Clim. Policy* **20**, S1–S13 (2020).

21. Owen, A. E. Techniques for evaluating the differences in consumption-based accounts. (University of Leeds, 2015).

22. Yang, Y. *et al.* Mapping global carbon footprint in China. *Nat. Commun.* **11**, 1–8 (2020).

23. Malek, Ž. & Verburg, P. H. Mapping global patterns of land use decision-making. *Glob. Environ. Chang.* **65**, 102170 (2020).

24. Meijaard, E. *et al. Oil palm and biodiversity: a situation analysis*. *IUCN Oil Palm Task Force* (2018) doi:10.2305/iucn.ch.2018.11.en.

25. Grassini, P., Specht, J. E., Tollenaar, M., Ciampitti, I. & Cassman, K. G. High-yield maize-soybean cropping systems in the US Corn Belt. in *Crop Physiology: Applications for Genetic Improvement and Agronomy: Second Edition* 17–41 (Elsevier Inc., 2015). doi:10.1016/B978-0-12-417104-6.00002-9.

26. Yu, Q. *et al.* A cultivated planet in 2010 – Part 2: The global gridded agricultural-production maps. *Earth Syst. Sci. Data* **12**, 3545–3572 (2020).

27. Buchhorn, M. *et al.* Copernicus Global Land Service: Land Cover 100m: collection 3: epoch 2019: Globe. (2020) doi:10.5281/ZENODO.3939050.

28. Jun, C., Ban, Y. & Li, S. Open access to Earth land-cover map. *Nature* vol. 514 434 (2014).

29. Li, W. *et al.* Gross and net land cover changes in the main plant functional types derived from the annual ESA CCI land cover maps (1992–2015). *Earth Syst. Sci. Data* **10**, 219 (2018).

30. Channan, S., Collins, K. & Emanuel, W. R. Global mosaics of the standard MODIS land cover type data. *Univ. Maryl. Pacific Northwest Natl. Lab. Coll. Park. Maryland, USA* **30**, (2014).

31. Eros, U., Falls, S. & South, D. *NASA Making Earth System Data Records for Use in Research Environments (MEaSUREs) Global Food Security-support Analysis Data (GFSAD) @ 30-m for Southeast and Northeast Asia Cropland Extent-Product (GFSAD30SEACE) User Guide*. (2018).

32. Pfister, S., Bayer, P., Koehler, A. & Hellweg, S. Environmental impacts of water use in global crop production: Hotspots and trade-offs with land use. *Environ. Sci. Technol.* **45**, 5761–5768 (2011).

33. Moran, D. & Kanemoto, K. Identifying species threat hotspots from global supply chains. *Nat. Ecol. Evol.* **1**, 23 (2017).

34. Sun, Z., Tukker, A. & Behrens, P. Going Global to Local: Connecting Top-Down Accounting and Local Impacts, A Methodological Review of Spatially Explicit Input-Output Approaches. *Environmental Science and Technology* vol. 53 1048–1062 (2019).

35. Ramankutty, N., Evan, A. T., Monfreda, C. & Foley, J. A. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Global Biogeochem. Cycles* **22**, n/a-n/a (2008).

36. Bruckner, M. *et al.* FABIO - The Construction of the Food and Agriculture Biomass Input-Output Model. *Environ. Sci. Technol.* **53**, 11302–11312 (2019).

37. Poore, J. & Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science (80-.).* **360**, 987–992 (2018).

38. Ceballos, G. *et al.* Accelerated modern human-induced species losses: Entering the sixth mass extinction. *Sci. Adv.* **1**, e1400253 (2015).

39. Pimm, S. L. *et al.* The biodiversity of species and their rates of extinction, distribution, and protection. *Science (80-.).* **344**, 1246752–1246752 (2014).

40. IPBES. *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. (2019).

41. Díaz, S. *et al.* Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science* vol. 366 (2019).

42. Clark, M. A. *et al.* Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. *Science (80-.).* **370**, 705–708 (2020).

43. Mottet, A. *et al.* Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. *Global Food Security* vol. 14 1–8 (2017).

44. Shepon, A., Eshel, G., Noor, E. & Milo, R. Energy and protein feed-to-food conversion efficiencies in the US and potential food security gains from dietary changes. *Environ. Res. Lett.* **11**, 105002 (2016).

45. Godfray, H. C. J. *et al.* Meat consumption, health, and the environment. *Science* vol. 361 (2018).

46. Clark, M. A., Springmann, M., Hill, J. & Tilman, D. Multiple health and environmental impacts of foods. *Proc. Natl. Acad. Sci. U. S. A.* **116**, 23357–23362 (2019).

47. Foley, J. A. *et al.* Solutions for a cultivated planet. *Nature* **478**, 337–342 (2011).

48. Pingali, P. L. Green revolution: Impacts, limits, andthe path ahead. *Proceedings of the National Academy of Sciences of the United States of America* vol. 109 12302–12308 (2012).

49. Fears, R., Canales Holzeis, C. & ter Meulen, V. Designing inter-regional engagement to inform cohesive policy making. *Palgrave Communications* vol. 6 1–5 (2020).

50. Lutter, S., Pfister, S., Giljum, S., Wieland, H. & Mutel, C. Spatially explicit assessment of water embodied in European trade: A product-level multi-regional input-output analysis. *Glob. Environ. Chang.* **38**, 171–182 (2016).

51. Behrens, P. *et al.* Evaluating the environmental impacts of dietary recommendations. *Proc. Natl. Acad. Sci. U. S. A.* **114**, 13412–13417 (2017).

52. Wiedmann, T., Lenzen, M., Turner, K. & Barrett, J. Examining the global environmental impact of regional consumption activities—Part 2: Review of input–output models for the assessment of environmental impacts embodied in trade. *Ecol. Econ.* **61**, 15–26 (2007).

53. Hertwich, E. G. & Peters, G. P. Carbon footprint of nations: A global, trade-linked analysis. *Environ. Sci. Technol.* **43**, 6414–6420 (2009).

54. Weber, C. L. & Matthews, H. S. Embodied environmental emissions in US international trade, 1997− 2004. (2007).

55. Guan, D. *et al.* The socioeconomic drivers of China's primary PM2. 5 emissions. *Environ. Res. Lett.* **9**, 24010 (2014).

56. Takase, K., Kondo, Y. & Washizu, A. An analysis of sustainable consumption by the waste Input-Output model. *J. Ind. Ecol.* **9**, 201–219 (2005).

57. Zhao, X. *et al.* Physical and virtual water transfers for regional water stress alleviation in China. *Proc. Natl. Acad. Sci.* **112**, 1031–1035 (2015).

58. Yu, Y., Feng, K. & Hubacek, K. Tele-connecting local consumption to global land use. *Glob. Environ. Chang.* **23**, 1178–1186 (2013).

59. Lenzen, M. *et al.* International trade drives biodiversity threats in developing nations. *Nature* **486**, 109–112 (2012).

60. Tukker, A. *et al.* Environmental and resource footprints in a global context: Europe's

structural deficit in resource endowments. *Glob. Environ. Chang.* **40**, 171–181 (2016).

61. Yuan, R., Behrens, P. & Rodrigues, J. F. D. The evolution of inter-sectoral linkages in China's energy-related CO2 emissions from 1997 to 2012. *Energy Econ.* **69**, 404–417 (2018).

62. Moran, D., Petersone, M. & Verones, F. On the suitability of input–output analysis for calculating product-specific biodiversity footprints. *Ecol. Indic.* **60**, 192–201 (2016).

63. Peters, G. P. From production-based to consumption-based national emission inventories. *Ecol. Econ.* **65**, 13–23 (2008).

64. Yuan, R., Behrens, P., Tukker, A. & Rodrigues, J. F. D. Carbon overhead: The impact of the expansion in low-carbon electricity in China 2015–2040. *Energy Policy* **119**, 97–104 (2018).

65. Wiedmann, T. A review of recent multi-region input–output models used for consumption-based emission and resource accounting. *Ecol. Econ.* **69**, 211–222 (2009).

66. Marques, A., Rodrigues, J., Lenzen, M. & Domingos, T. Income-based environmental responsibility. *Ecol. Econ.* **84**, 57–65 (2012).

67. Behrens, P., Rodrigues, J. F. D., Brás, T. & Silva, C. Environmental, economic, and social impacts of feed-in tariffs: A Portuguese perspective 2000–2010. *Appl. Energy* **173**, 309–319 (2016).

68. Liang, S., Qu, S. & Xu, M. Betweenness-Based Method to Identify Critical Transmission Sectors for Supply Chain Environmental Pressure Mitigation. *Environ. Sci. Technol.* **50**, 1330–1337 (2016).

69. Janssens-Maenhout, G. *et al.* EDGAR v4. 3.2 Global Atlas of the three major Greenhouse Gas Emissions for the period 1970–2012. *Earth Syst. Sci. Data Discuss* (2017).

70. Flörke, M. *et al.* Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. *Glob. Environ. Chang.* **23**, 144–156 (2013).

71. van Vliet, M. T. H., Flörke, M. & Wada, Y. Quality matters for water scarcity. *Nat. Geosci.* **10**, 800 (2017).

72. IUCN. The IUCN red list of threatened species: 2015-14. (2015).

73. International, B. IUCN Red List for birds. (2013).

74. Beer, C. *et al.* Terrestrial gross carbon dioxide uptake: global distribution and covariation with climate. *Science (80-.).* **329**, 834–838 (2010).

75. Van Donkelaar, A., Martin, R. V, Brauer, M. & Boys, B. L. Use of satellite observations

for long-term exposure assessment of global concentrations of fine particulate matter. *Environ. Health Perspect.* **123**, 135 (2015).

76. Friedl, M. A. *et al.* MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets. *Remote Sens. Environ.* **114**, 168–182 (2010).

77. Teng, Y. *et al.* Soil and soil environmental quality monitoring in China: a review. *Environ. Int.* **69**, 177–199 (2014).

78. Lloyd, C. E. M., Freer, J. E., Johnes, P. J. & Collins, A. L. Using hysteresis analysis of high-resolution water quality monitoring data, including uncertainty, to infer controls on nutrient and sediment transfer in catchments. *Sci. Total Environ.* **543**, 388–404 (2016).

79. Lamarche, C. *et al.* Compilation and validation of SAR and optical data products for a complete and global map of inland/ocean water tailored to the climate modeling community. *Remote Sens.* **9**, 36 (2017).

80. Meyer, C., Kreft, H., Guralnick, R. & Jetz, W. Global priorities for an effective information basis of biodiversity distributions. *Nat. Commun.* **6**, (2015).

81. Rost, S. *et al.* Agricultural green and blue water consumption and its influence on the global water system. *Water Resour. Res.* **44**, (2008).

82. Alcamo, J. *et al.* Development and testing of the WaterGAP 2 global model of water use and availability. *Hydrol. Sci. J.* **48**, 317–337 (2003).

83. Hansen, K. M., Christensen, J. H., Brandt, J., Frohn, L. M. & Geels, C. Modelling atmospheric transport of α-hexachlorocyclohexane in the Northern Hemispherewith a 3-D dynamical model: DEHM-POP. *Atmos. Chem. Phys.* **4**, 1125–1137 (2004).

84. Klein Goldewijk, K., Beusen, A., Van Drecht, G. & De Vos, M. The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. *Glob. Ecol. Biogeogr.* **20**, 73–86 (2011).

85. Hoekstra, A. Y. & Wiedmann, T. O. Humanity's unsustainable environmental footprint. *Science (80-.).* **344**, 1114–1117 (2014).

86. Hoekstra, A. Y. & Mekonnen, M. M. The water footprint of humanity. *Proc. Natl. Acad. Sci.* **109**, 3232–3237 (2012).

87. Mekonnen, M. & Hoekstra, A. Y. The green, blue and grey water footprint of crops and derived crops products. *Hydrol. earth Syst. Sci. Discuss.* **8**, 763–809 (2011).

88. Wang, Y. *et al.* Spatial production fragmentation and PM2.5 related emissions transfer through three different trade patterns within China. *J. Clean. Prod.* **195**, 703–720 (2018).

89. Ridoutt, B. G., Hadjikakou, M., Nolan, M. & Bryan, B. A. From Water-Use to Water-Scarcity Footprinting in Environmentally Extended Input–Output Analysis. *Environ. Sci. Technol.* **52**, 6761–6770 (2018).

90. Wilting, H. C., Schipper, A. M., Bakkenes, M., Meijer, J. R. & Huijbregts, M. A. J. Quantifying Biodiversity Losses Due to Human Consumption: A Global-Scale Footprint Analysis. *Environ. Sci. Technol.* **51**, 3298–3306 (2017).

91. Verones, F., Moran, D., Stadler, K., Kanemoto, K. & Wood, R. Resource footprints and their ecosystem consequences. *Sci. Rep.* **7**, 40743 (2017).

92. Ploszaj, A., Celinska-Janowicz, D., Rok, J. & Zawalinska, K. *Regional Input-Output Studies: A Systematic Literature Review*. (2015).

93. James, D. E., Chambers, J. A., Kalma, J. D. & Bridgman, H. A. Air quality prediction in urban and semi-urban regions with generalised input–output analysis: the Hunter Region, Australia. *Urban Ecol.* **9**, 25–44 (1985).

94. Gassert, F., Landis, M., Luck, M., Reig, P. & Shiao, T. Aqueduct global maps 2.0. *Water Resour. Inst. Washington, DC* 202011–202012 (2013).

95. Kanemoto, K., Moran, D. & Hertwich, E. G. Mapping the carbon footprint of nations. *Environ. Sci. Technol.* **50**, 10512–10517 (2016).

96. Moran, D. & Kanemoto, K. Tracing global supply chains to air pollution hotspots. *Environ. Res. Lett.* **11**, 94017 (2016).

97. Wang, R., Zimmerman, J., Wangt, R. & Zimmerman, J. Hybrid Analysis of Blue Water Consumption and Water Scarcity Implications at the Global, National, and Basin Levels in an Increasingly Globalized World. *Environ. Sci. Technol.* **50**, 5143–5153 (2016).

98. Lin, J. *et al.* China's international trade and air pollution in the United States. *Proc. Natl. Acad. Sci.* **111**, 1736–1741 (2014).

99. Wang, H. *et al.* Trade-driven relocation of air pollution and health impacts in China. *Nat. Commun.* **8**, 738 (2017).

100. Chen, L. *et al.* Trade-induced atmospheric mercury deposition over China and implications for demand-side controls. *Environ. Sci. Technol.* **52**, 2036–2045 (2018).

101. Zhao, H. *et al.* Effects of atmospheric transport and trade on air pollution mortality in China. *Atmos. Chem. Phys.* **17**, 10367–10381 (2017).

102. Lin, J. *et al.* Global climate forcing of aerosols embodied in international trade. *Nat. Geosci.* **9**, 790 (2016).

103. Jiang, X. *et al.* Revealing the hidden health costs embodied in Chinese exports. *Environ. Sci. Technol.* **49**, 4381–4388 (2015).

104. Zhang, Q. *et al.* Transboundary health impacts of transported global air pollution and international trade. *Nature* **543**, 705–709 (2017).

105. Ivanova, D. *et al.* Mapping the carbon footprint of EU regions. *Environ. Res. Lett.* **12**,

54013 (2017).

106. Marin, G. & Modica, M. Socio-economic exposure to natural disasters. *Environ. Impact Assess. Rev.* **64**, 57–66 (2017).

107. Moran, D. *et al.* Carbon footprints of 13 000 cities. *Environ. Res. Lett.* **13**, 064041 (2018).

108. Feng, K. *et al.* Spatially Explicit Analysis of Water Footprints in the UK. *Water* **3**, 47–63 (2011).

109. Godar, J., Persson, U. M., Tizado, E. J. & Meyfroidt, P. Towards more accurate and policy relevant footprint analyses: tracing fine-scale socio-environmental impacts of production to consumption. *Ecol. Econ.* **112**, 25–35 (2015).

110. Steen-Olsen, K., Wood, R. & Hertwich, E. G. The Carbon Footprint of Norwegian Household Consumption 1999-2012. *J. Ind. Ecol.* **20**, 582–592 (2016).

111. Malik, A., McBain, D., Wiedmann, T. O., Lenzen, M. & Murray, J. Advancements in Input-Output Models and Indicators for Consumption-Based Accounting. *J. Ind. Ecol.* (2018) doi:10.1111/jiec.12771.

112. Mi, Z. *et al.* A multi-regional input-output table mapping China's economic outputs and interdependencies in 2012. *Sci. Data* **5**, 180155 (2018).

113. Holland, R. A. *et al.* Global impacts of energy demand on the freshwater resources of nations. *Proc. Natl. Acad. Sci. U. S. A.* **112**, E6707–E6716 (2015).

114. Moran, D. & Kanemoto, K. Identifying species threat hotspots from global supply chains. *Nat. Ecol. Evol.* **1**, 23 (2017).

115. Mekonnen, M. M., Lutter, S. & Martinez, A. Anthropogenic Nitrogen and Phosphorus Emissions and Related Grey Water Footprints Caused by EU-27's Crop Production and Consumption. *Water* **8**, 30 (2016).

116. Cazcarro, I., Duarte, R., Sanchez-Choliz, J. & Sánchez Chóliz, J. Downscaling the grey water footprints of production and consumption. *J. Clean. Prod.* **132**, 171–183 (2016).

117. McDonald, G. W., Smith, N. J., Kim, J., Cronin, S. J. & Proctor, J. N. The spatial and temporal 'cost'of volcanic eruptions: assessing economic impact, business inoperability, and spatial distribution of risk in the Auckland region, New Zealand. *Bull. Volcanol.* **79**, 48 (2017).

118. Kim, J. H. & Hewings, G. J. D. Integrating the fragmented regional and subregional socioeconomic forecasting and analysis: a spatial regional econometric input-output framework. *Ann. Reg. Sci.* **49**, 485–513 (2012).

119. Zhou, X., Lei, K., Khu, S.-T. T. & Meng, W. Spatial flow analysis of water pollution in eco-natural systems. *Ecol. Indic.* **69**, 310–317 (2016).

120. Zhou, X., Lei, K., Meng, W. & Khu, S.-T. T. Industrial structural upgrading and spatial optimization based on water environment carrying capacity. *J. Clean. Prod.* **165**, 1462–1472 (2017).

121. Van Der Veen, A. & Logtmeijer, C. Economic hotspots: visualizing vulnerability to flooding. *Nat. hazards* **36**, 65–80 (2005).

122. Long, Y., Yoshida, Y. & Dong, L. Exploring the indirect household carbon emissions by source: Analysis on 49 Japanese cities. *J. Clean. Prod.* **167**, 571–581 (2017).

123. Zhang, Z. *et al.* Assessment of the ripple effects and spatial heterogeneity of total losses in the capital of China after a great catastrophic shock. *Nat. Hazards Earth Syst. Sci.* **17**, 367 (2017).

124. Larsen, H. N. & Hertwich, E. G. Identifying important characteristics of municipal carbon footprints. *Ecol. Econ.* **70**, 60–66 (2010).

125. Larsen, H. N. & Hertwich, E. G. Analyzing the carbon footprint from public services provided by counties. *J. Clean. Prod.* **19**, 1975–1981 (2011).

126. Minx, J. *et al.* Carbon footprints of cities and other human settlements in the UK. *Environ. Res. Lett.* **8**, 35039 (2013).

127. Baiocchi, G., Minx, J. & Hubacek, K. The impact of social factors and consumer behavior on carbon dioxide emissions in the United Kingdom. *J. Ind. Ecol.* **14**, 50–72 (2010).

128. Poom, A. & Ahas, R. How Does the Environmental Load of Household Consumption Depend on Residential Location? *Sustainability* **8**, 799 (2016).

129. Lenzen, M., Dey, C. & Foran, B. Energy requirements of Sydney households. *Ecol. Econ.* **49**, 375–399 (2004).

130. Chen, G., Hadjikakou, M., Wiedmann, T. & Shi, L. Global warming impact of suburbanization: The case of Sydney. *J. Clean. Prod.* **172**, 287–301 (2018).

131. Lenzen, M. & Peters, G. M. How city dwellers affect their resource hinterland. *J. Ind. Ecol.* **14**, 73–90 (2010).

132. Baynes, T., Lenzen, M., Steinberger, J. K. & Bai, X. Comparison of household consumption and regional production approaches to assess urban energy use and implications for policy. *Energy Policy* **39**, 7298–7309 (2011).

133. Isman, M. *et al.* Ecological Footprint assessment for targeting climate change mitigation in cities: A case study of 15 Canadian cities according to census metropolitan areas. *J. Clean. Prod.* **174**, 1032–1043 (2018).

134. Jones, C. M. & Kammen, D. M. Quantifying Carbon Footprint Reduction Opportunities for U.S. Households and Communities. *Environ. Sci. Technol.* **45**, 4088–4095 (2011).

135. Baabou, W., Grunewald, N., Ouellet-Plamondon, C., Gressot, M. & Galli, A. The Ecological Footprint of Mediterranean cities: Awareness creation and policy implications. *Environ. Sci. Policy* **69**, 94–104 (2017).

136. Ottelin, J., Heinonen, J. & Junnila, S. Carbon footprint trends of metropolitan residents in Finland: How strong mitigation policies affect different urban zones. *J. Clean. Prod.* **170**, 1523–1535 (2018).

137. Thomas, B. A., Hausfather, Z. & Azevedo, I. L. Comparing the magnitude of simulated residential rebound effects from electric end-use efficiency across the US. *Environ. Res. Lett.* **9**, 074010 (2014).

138. Liu, L. *et al.* Assessment and determinants of per capita household CO2 emissions (PHCEs) based on capital city level in China. *J. Geogr. Sci.* **28**, 1467–1484 (2018).

139. Gill, B. & Moeller, S. GHG Emissions and the Rural-Urban Divide. A Carbon Footprint Analysis Based on the German Official Income and Expenditure Survey. *Ecol. Econ.* **145**, 160–169 (2018).

140. Laine, J. *et al.* Consequential Implications of Municipal Energy System on City Carbon Footprints. *Sustainability* **9**, 1801 (2017).

141. Goldstein, B. P., Hauschild, M. Z., Fernández, J. E. & Birkved, M. Contributions of Local Farming to Urban Sustainability in the Northeast United States. *Environ. Sci. Technol.* **51**, 7340–7349 (2017).

142. Han, L., Xu, X. & Han, L. Applying quantile regression and Shapley decomposition to analyzing the determinants of household embedded carbon emissions: evidence from urban China. *J. Clean. Prod.* **103**, 219–230 (2015).

143. Jones, C. & Kammen, D. M. Spatial distribution of US household carbon footprints reveals suburbanization undermines greenhouse gas benefits of urban population density. *Environ. Sci. Technol.* **48**, 895–902 (2014).

144. Jones, C. M., Wheeler, S. M. & Kammen, D. M. Carbon Footprint Planning: Quantifying Local and State Mitigation Opportunities for 700 California Cities. *Urban Plan.* **3**, 35 (2018).

145. Boero, R., Edwards, B. K. & Rivera, M. K. Regional input–output tables and trade flows: an integrated and interregional non-survey approach. *Reg. Stud.* **52**, 225–238 (2018).

146. Faturay, F., Lenzen, M. & Nugraha, K. A new sub-national multi-region input–output database for Indonesia. *Econ. Syst. Res.* **29**, 234–251 (2017).

147. Jahn, M. Extending the FLQ formula: a location quotient-based interregional input–output framework. *Reg. Stud.* **51**, 1518–1529 (2017).

148. Sargento, A. L. M., Ramos, P. N. & Hewings, G. J. D. Inter-regional Trade Flow Estimation Through Non-Survey Models: An Empirical Assessment. *Econ. Syst. Res.* **24**,

173–193 (2012).

149. Többen, J. & Kronenberg, T. H. Construction of Multiregional Input–Ouptput Tables Using The CHARM Method. *Econ. Syst. Res.* **27**, 487–507 (2015).

150. Lenzen, M. *et al.* Compiling and using input–output frameworks through collaborative virtual laboratories. *Sci. Total Environ.* **485–486**, 241–251 (2014).

151. Hasegawa, R., Kagawa, S. & Tsukui, M. Carbon footprint analysis through constructing a multi-region input–output table: a case study of Japan. *J. Econ. Struct.* **4**, 5 (2015).

152. Cazcarro, I., Duarte, R. & Sánchez Chóliz, J. Multiregional Input–Output Model for the Evaluation of Spanish Water Flows. *Environ. Sci. Technol.* **47**, 12275–12283 (2013).

153. Flach, R., Ran, Y., Godar, J., Karlberg, L. & Suavet, C. Towards more spatially explicit assessments of virtual water flows: linking local water use and scarcity to global demand of Brazilian farming commodities. *Environ. Res. Lett.* **11**, 75003 (2016).

154. Godar, J., Suavet, C., Gardner, T. A., Dawkins, E. & Meyfroidt, P. Balancing detail and scale in assessing transparency to improve the governance of agricultural commodity supply chains. *Environ. Res. Lett.* **11**, 35015 (2016).

155. Lenzen, M. *et al.* New multi-regional input–output databases for Australia – enabling timely and flexible regional analysis. *Econ. Syst. Res.* **29**, 275–295 (2017).

156. Davis, S. J., Peters, G. P. & Caldeira, K. The supply chain of CO_2 emissions. *Proc. Natl. Acad. Sci.* **108**, 18554–18559 (2011).

157. You, L., Wood, S., Wood-Sichra, U. & Wu, W. Generating global crop distribution maps: From census to grid. *Agric. Syst.* **127**, 53–60 (2014).

158. Robinson, T. P. *et al.* Mapping the Global Distribution of Livestock. *PLoS One* **9**, e96084 (2014).

159. Tong, D. *et al.* Targeted emission reductions from global super-polluting power plant units. *Nat. Sustain.* **1**, 59 (2018).

160. Platnick, S. *the earth observer National Aeronautics and Space Administration The Earth Observer*. vol. 30.

161. Meijer, J. R., Huijbregts, M. A. J., Schotten, K. C. G. J. & Schipper, A. M. Global patterns of current and future road infrastructure. *Environ. Res. Lett.* **13**, 064006 (2018).

162. Verburg, P. H., Ellis, E. C. & Letourneau, A. A global assessment of market accessibility and market influence for global environmental change studies. *Environ. Res. Lett.* **6**, 034019 (2011).

163. SECEX. SISCOMEX system. *Secretariat of Foreign Trade of the Brazilian Ministry of Development, Industry and Foreign Trade* (2018).

164. Kirches, G. *et al.* Land Cover CCI-Product User Guide-Version 2. *ESA Public Doc. CCI-LC-PUG* 4 (2014).

165. Teluguntla, P. *et al.* Global Food Security Support Analysis Data (GFSAD) at Nominal 1 km (GCAD) Derived from Remote Sensing in Support of Food Security in the Twenty-First Century: Current Achievements and Future Possibilities. (2015).

166. Gassert, F., Luck, M., Landis, M., Reig, P. & Shiao, T. Aqueduct global maps 2.1: Constructing decision-relevant global water risk indicators. *World Resour. Inst.* (2014).

167. Sood, A. & Smakhtin, V. Global hydrological models: a review. *Hydrol. Sci. J.* **60**, 549–565 (2015).

168. Nakagaki, N. *Grids of agricultural pesticide use in the conterminous United States, 1997*. (2007).

169. Rondinini, C. *et al.* Global habitat suitability models of terrestrial mammals. *Philos. Trans. R. Soc. B Biol. Sci.* **366**, 2633–2641 (2011).

170. Rosenzweig, C. *et al.* Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proc. Natl. Acad. Sci.* **111**, 3268–3273 (2014).

171. You, L. *et al.* Spatial production allocation model (SPAM) 2005 v2. 0. *Available mapspam. info. Accessed June* **29**, 2015 (2014).

172. Arrouays, D. *et al.* GlobalSoilMap for Soil Organic Carbon Mapping and as a Basis for Global Modeling. in *Proceedings of the global symposium on soil organic carbon 2017* 27–30 (2017).

173. Kshetri, N. 1 Blockchain's roles in meeting key supply chain management objectives. *Int. J. Inf. Manage.* **39**, 80–89 (2018).

174. Hubacek, K., Feng, K., Minx, J., Pfister, S. & Zhou, N. Teleconnecting consumption to environmental impacts at multiple spatial scales–research frontiers in environmental footprinting. *J. Ind. Ecol.* **18**, 7–9 (2014).

175. Tukker, A. *et al.* Towards Robust, Authoritative Assessments of Environmental Impacts Embodied in Trade: Current State and Recommendations. *J. Ind. Ecol.* **22**, 585–598 (2018).

176. Riddington, G., Gibson, H. & Anderson, J. Comparison of Gravity Model, Survey and Location Quotient-based Local Area Tables and Multipliers. *Reg. Stud.* **40**, 1069–1081 (2006).

177. Hirbli, T. *Palm Oil traceability: Blockchain meets supply chain*. (2018).

178. Behrens, P., van Vliet, M. T. H., Nanninga, T., Walsh, B. & Rodrigues, J. F. D. Climate change and the vulnerability of electricity generation to water stress in the European

Union. *Nat. Energy* **2**, 17114 (2017).

179. Su, B., Huang, H. C., Ang, B. W. & Zhou, P. Input–output analysis of CO 2 emissions embodied in trade: the effects of sector aggregation. *Energy Econ.* **32**, 166–175 (2010).

180. Wiedmann, T. O. *et al.* The material footprint of nations. *Proc. Natl. Acad. Sci.* **112**, 6271–6276 (2015).

181. Su, B. & Ang, B. W. Input–output analysis of CO 2 emissions embodied in trade: the effects of spatial aggregation. *Ecol. Econ.* **70**, 10–18 (2010).

182. Dietzenbacher, E. *et al.* Input–output analysis: the next 25 years. *Econ. Syst. Res.* **25**, 369–389 (2013).

183. Mattila, T., Koskela, S., Seppälä, J. & Mäenpää, I. Sensitivity analysis of environmentally extended input–output models as a tool for building scenarios of sustainable development. *Ecol. Econ.* **86**, 148–155 (2013).

184. Wu, X. & Chen, G. Energy use by Chinese economy: A systems cross-scale input-output analysis. *Energy Policy* **108**, 81–90 (2017).

185. Benz, U. C., Hofmann, P., Willhauck, G., Lingenfelder, I. & Heynen, M. Multi-resolution, object-oriented fuzzy analysis of remote sensing data for GIS-ready information. *ISPRS J. Photogramm. Remote Sens.* **58**, 239–258 (2004).

186. Sandefur, J. & Glassman, A. The political economy of bad data: evidence from African survey and administrative statistics. *J. Dev. Stud.* **51**, 116–132 (2015).

187. Lenzen, M., Wood, R. & Wiedmann, T. Uncertainty analysis for multi-region input–output models–a case study of the UK's carbon footprint. *Econ. Syst. Res.* **22**, 43–63 (2010).

188. Karstensen, J., Peters, G. P. & Andrew, R. M. Uncertainty in temperature response of current consumption-based emissions estimates. *Earth Syst. Dyn.* **6**, 287 (2015).

189. Wiedmann, T., Wood, R., Minx, J., Lenzen, M. & Harris, R. Emissions embedded in UK trade–UK-MRIO model results and error estimates. in *International input–output meeting on managing the environment* 9–11 (2008).

190. Bullard, C. W. & Sebald, A. V. Monte Carlo sensitivity analysis of input-output models. *Rev. Econ. Stat.* 708–712 (1988).

191. Oita, A. *et al.* Substantial nitrogen pollution embedded in international trade. *Nat. Geosci.* **9**, 111–115 (2016).

192. Wilting, H. C. Sensitivity and uncertainty analysis in mrio modelling; some empirical results with regard to the dutch carbon footprint. *Econ. Syst. Res.* **24**, 141–171 (2012).

193. Yan, J., Zhao, T. & Kang, J. Sensitivity analysis of technology and supply change for

CO 2 emission intensity of energy-intensive industries based on input–output model. *Appl. Energy* **171**, 456–467 (2016).

194. Lenzen, M. Errors in conventional and Input-Output—based Life—Cycle inventories. *J. Ind. Ecol.* **4**, 127–148 (2000).

195. Rodrigues, J. F. D., Moran, D., Wood, R. & Behrens, P. Uncertainty of Consumption-Based Carbon Accounts. *Environ. Sci. Technol.* **52**, 7577–7586 (2018).

196. Stehfest, E., van Vuuren, D., Bouwman, L. & Kram, T. *Integrated assessment of global environmental change with IMAGE 3.0: Model description and policy applications*. (Netherlands Environmental Assessment Agency (PBL), 2014).

197. West, T. O., Le Page, Y., Huang, M., Wolf, J. & Thomson, A. M. Downscaling global land cover projections from an integrated assessment model for use in regional analyses: results and evaluation for the US from 2005 to 2095. *Environ. Res. Lett.* **9**, 64004 (2014).

198. Hasegawa, T., Fujimori, S., Ito, A., Takahashi, K. & Masui, T. Global land-use allocation model linked to an integrated assessment model. *Sci. Total Environ.* **580**, 787–796 (2017).

199. Hurtt, G. C. *et al.* Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. *Clim. Change* **109**, 117 (2011).

200. Humpenöder, F. *et al.* Land-use and carbon cycle responses to moderate climate change: implications for land-based mitigation? *Environ. Sci. Technol.* **49**, 6731–6739 (2015).

201. Fujimori, S. *et al.* Downscaling Global Emissions and Its Implications Derived from Climate Model Experiments. *PLoS One* **12**, e0169733 (2017).

202. Hellmann, F. & Verburg, P. H. Spatially explicit modelling of biofuel crops in Europe. *Biomass and Bioenergy* **35**, 2411–2424 (2011).

203. Verburg, P. H., Eickhout, B. & van Meijl, H. A multi-scale, multi-model approach for analyzing the future dynamics of European land use. *Ann. Reg. Sci.* **42**, 57–77 (2008).

204. Hurtt, G. C. *et al.* The underpinnings of land-use history: Three centuries of global gridded land-use transitions, wood-harvest activity, and resulting secondary lands. *Glob. Chang. Biol.* **12**, 1208–1229 (2006).

205. Thomson, A. M. *et al.* Climate mitigation and the future of tropical landscapes. *Proc. Natl. Acad. Sci.* **107**, 19633–19638 (2010).

206. Kraucunas, I. *et al.* Investigating the nexus of climate, energy, water, and land at decision-relevant scales: the Platform for Regional Integrated Modeling and Analysis (PRIMA). *Clim. Change* **129**, 573–588 (2015).

207. Hejazi, M. I. *et al.* Integrated assessment of global water scarcity over the 21st century under multiple climate change mitigation policies. *Hydrol. Earth Syst. Sci.* **18**, 2859–

2883 (2014).

208. Voisin, N. *et al.* Effects of spatially distributed sectoral water management on the redistribution of water resources in an integrated water model. *Water Resour. Res.* **53**, 4253–4270 (2017).

209. Müller, C. *et al.* Drivers and patterns of land biosphere carbon balance reversal. *Environ. Res. Lett.* **11**, 44002 (2016).

210. Pauliuk, S., Arvesen, A., Stadler, K. & Hertwich, E. G. Industrial ecology in integrated assessment models. *Nat. Clim. Chang.* **7**, 13–20 (2017).

211. Wiebe, K. S. The impact of renewable energy diffusion on European consumption-based emissions. *Econ. Syst. Res.* **28**, 133–150 (2016).

212. De Koning, A., Huppes, G., Deetman, S. & Tukker, A. Scenarios for a 2 °C world: a trade-linked input–output model with high sector detail. *Clim. Policy* **16**, 301–317 (2016).

213. Meyfroidt, P. Trade-offs between environment and livelihoods: Bridging the global land use and food security discussions. *Glob. Food Sec.* **16**, 9–16 (2018).

214. Godfray, H. C. J. *et al.* Food Security: The Challenge of Feeding 9 Billion People. *Science (80-.).* **327**, 812–818 (2010).

215. UN. *World Population Prospects 2019:Highlights*. (2019).

216. FAO. *The future of food and agriculture – Alternative pathways to 2050*. (2018) doi:CC BY-NC-SA 3.0 IGO.

217. Pellegrini, P. & Fernández, R. J. Crop intensification, land use, and on-farm energy-use efficiency during the worldwide spread of the green revolution. **6**, 2335–2340 (2018).

218. Wood, S. A., Smith, M. R., Fanzo, J., Remans, R. & DeFries, R. S. Trade and the equitability of global food nutrient distribution. *Nat. Sustain.* **1**, 34–37 (2018).

219. Alston, J. M., Beddow, J. M. & Pardey, P. G. Agricultural research, productivity, and food prices in the long run. *Science (80-.).* **325**, 1209–1210 (2009).

220. Ray, D. K., Mueller, N. D., West, P. C. & Foley, J. A. Yield trends are insufficient to double global crop production by 2050. *PLoS One* **8**, e66428 (2013).

221. Ray, D. K., Ramankutty, N., Mueller, N. D., West, P. C. & Foley, J. A. Recent patterns of crop yield growth and stagnation. *Nat. Commun.* **3**, 1293 (2012).

222. Springmann, M. *et al.* Options for keeping the food system within environmental limits. *Nature* **562**, 519–525 (2018).

223. Bruckner, M. *et al.* Quantifying the global cropland footprint of the European Union's non-food bioeconomy. *Environ. Res. Lett.* (2019) doi:10.1088/1748-9326/ab07f5.

224. Wang, R. & Zimmerman, J. Hybrid Analysis of Blue Water Consumption and Water Scarcity Implications at the Global, National, and Basin Levels in an Increasingly Globalized World. *Environ. Sci. Technol.* **50**, 5143–5153 (2016).

225. Henning, S. *et al.* Livestock's long shadow–environmental issues and options. *Roma, IT, FAO* (2006).

226. Van Boeckel, T. P. *et al.* Global trends in antimicrobial use in food animals. *Proc. Natl. Acad. Sci. U. S. A.* **112**, 5649–54 (2015).

227. Xue, L. *et al.* Missing Food, Missing Data? A Critical Review of Global Food Losses and Food Waste Data. *Environ. Sci. Technol.* **51**, 6618–6633 (2017).

228. Lesk, C., Rowhani, P. & Ramankutty, N. Influence of extreme weather disasters on global crop production. *Nature* **529**, 84–87 (2016).

229. Green, R. E., Cornell, S. J., Scharlemann, J. P. W. & Balmford, A. Farming and the fate of wild nature. *Science (80-.).* **307**, 550–555 (2005).

230. Balmford, A., Green, R. & Scharlemann, J. P. W. Sparing land for nature: exploring the potential impact of changes in agricultural yield on the area needed for crop production. *Glob. Chang. Biol.* **11**, 1594–1605 (2005).

231. Scherer, L. *et al.* Trade-offs between social and environmental Sustainable Development Goals. *Environ. Sci. Policy* **90**, 65–72 (2018).

232. Lambin, E. F. & Meyfroidt, P. Global land use change, economic globalization, and the looming land scarcity. *Proc. Natl. Acad. Sci. U. S. A.* **108**, 3465–72 (2011).

233. Kissinger, M. International trade related food miles–The case of Canada. *Food Policy* **37**, 171–178 (2012).

234. Fader, M., Gerten, D., Krause, M., Lucht, W. & Cramer, W. Spatial decoupling of agricultural production and consumption: quantifying dependences of countries on food imports due to domestic land and water constraints. *Environ. Res. Lett.* **8**, 14046 (2013).

235. D'Odorico, P., Carr, J. A., Laio, F., Ridolfi, L. & Vandoni, S. Feeding humanity through global food trade. *Earth's Futur.* **2**, 458–469 (2014).

236. Barona, E., Ramankutty, N., Hyman, G. & Coomes, O. T. The role of pasture and soybean in deforestation of the Brazilian Amazon. *Environ. Res. Lett.* **5**, 024002 (2010).

237. Lapola, D. M. *et al.* Pervasive transition of the Brazilian land-use system. *Nat. Clim. Chang.* **4**, 27–35 (2014).

238. Naylor, R. L. Oil crops, aquaculture, and the rising role of demand: A fresh perspective on food security. *Glob. Food Sec.* **11**, 17–25 (2016).

239. Austin, K. G. *et al.* Shifting patterns of oil palm driven deforestation in Indonesia and

implications for zero-deforestation commitments. *Land use policy* **69**, 41–48 (2017).

240. Suweis, S., Carr, J. A., Maritan, A., Rinaldo, A. & D'Odorico, P. Resilience and reactivity of global food security. *Proc. Natl. Acad. Sci. U. S. A.* **112**, 6902–7 (2015).

241. Stadler, K. *et al.* EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. *J. Ind. Ecol.* (2017).

242. Schulte-Mecklenbeck, M., Sohn, M., de Bellis, E., Martin, N. & Hertwig, R. A lack of appetite for information and computation. Simple heuristics in food choice. *Appetite* **71**, 242–251 (2013).

243. Tukker, A. & Dietzenbacher, E. Global multiregional input–output frameworks: an introduction and outlook. *Econ. Syst. Res.* **25**, 1–19 (2013).

244. Robinson, T. P. *et al.* Mapping the global distribution of livestock. *PLoS One* **9**, e96084 (2014).

245. Steffen, W. *et al.* Planetary boundaries: guiding human development on a changing planet. *Science* **347**, 1259855 (2015).

246. Campbell, B. M. *et al.* Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecol. Soc.* **22**, art8 (2017).

247. UNEP. *The Emissions Gap Report*. (2014).

248. IPCC. *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,*. (2018).

249. Hoekstra, A. Y. & Wiedmann, T. O. Humanity's unsustainable environmental footprint. *Science* **344**, 1114–7 (2014).

250. Bringezu, S. Possible Target Corridor for Sustainable Use of Global Material Resources. *Resources* **4**, 25–54 (2015).

251. FAOSTAT. FAOSTAT. (2019).

252. Willett, W. *et al.* Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet* **393**, 447–492 (2019).

253. Suweis, S., Carr, J. A., Maritana, A., Rinaldo, A. & D'Odorico, P. Resilience and reactivity of global food security. *Proc. Natl. Acad. Sci. U. S. A.* **112**, 6902–6907 (2015).

254. Behrens, P. *et al.* Evaluating the environmental impacts of dietary recommendations. *Proc. Natl. Acad. Sci.* **114**, 13412–13417 (2017).

255. Godar, J., Persson, U. M., Tizado, E. J. & Meyfroidt, P. Towards more accurate and

policy relevant footprint analyses: Tracing fine-scale socio-environmental impacts of production to consumption. *Ecol. Econ.* **112**, 25–35 (2015).

256. Google Map. World Ports.

257. Gardner, T. A. *et al.* Transparency and sustainability in global commodity supply chains. *World Dev.* **121**, 163–177 (2019).

258. Coates, J. Build it back better: Deconstructing food security for improved measurement and action. *Glob. Food Sec.* **2**, 188–194 (2013).

259. Chen, B. *et al.* Global land-water nexus: Agricultural land and freshwater use embodied in worldwide supply chains. *Sci. Total Environ.* **613–614**, 931–943 (2018).

260. Chen, G. & Han, M. Global supply chain of arable land use: Production-based and consumption-based trade imbalance. *Land use policy* **49**, 118–130 (2015).

261. Fuglie, K. O. Is agricultural productivity slowing? *Glob. Food Sec.* **17**, 73–83 (2018).

262. Rulli, M. C., Saviori, A., D'Odorico, P. & D'Odorico, P. Global land and water grabbing. *Proc. Natl. Acad. Sci.* **110**, 892–897 (2013).

263. Fukase, E. & Martin, W. Who will feed China in the 21st century? Income growth and food demand and supply in China. *J. Agric. Econ.* **67**, 3–23 (2016).

264. Yao, G., Hertel, T. W. & Taheripour, F. Economic drivers of telecoupling and terrestrial carbon fluxes in the global soybean complex. *Glob. Environ. Chang.* **50**, 190–200 (2018).

265. FAO, IFAD, UNICEF, WFP & WHO. *The State of Food Security and Nutrition in the World 2019. Safeguarding against economic slowdowns and downturns*. (FAO, 2019).

266. Scherer, L. & Pfister, S. Global Biodiversity Loss by Freshwater Consumption and Eutrophication from Swiss Food Consumption. *Environ. Sci. Technol.* **50**, 7019–7028 (2016).

267. Moran, D. & Kanemoto, K. Identifying species threat hotspots from global supply chains. *Nat. Ecol. Evol.* **1**, 0023 (2017).

268. Gilbert, M. *et al.* Global distribution data for cattle, buffaloes, horses, sheep, goats, pigs, chickens and ducks in 2010. *Sci. Data* **5**, 180227 (2018).

269. Smith, T. M. *et al.* Subnational mobility and consumption-based environmental accounting of US corn in animal protein and ethanol supply chains. *Proc. Natl. Acad. Sci. U. S. A.* **114**, E7891–E7899 (2017).

270. Sandström, V. *et al.* The role of trade in the greenhouse gas footprints of EU diets. *Glob. Food Sec.* **19**, 48–55 (2018).

271. Zuo, L. *et al.* Progress towards sustainable intensification in China challenged by land-

use change. *Nat. Sustain.* **1**, 304–313 (2018).

272. Carlson, K. M. *et al.* Greenhouse gas emissions intensity of global croplands. *Nat. Clim. Chang.* **7**, 63–68 (2017).

273. He, P., Baiocchi, G., Hubacek, K., Feng, K. & Yu, Y. The environmental impacts of rapidly changing diets and their nutritional quality in China. *Nat. Sustain.* **1**, 122–127 (2018).

274. Liu, J. *et al.* A high-resolution assessment on global nitrogen flows in cropland. *Proc. Natl. Acad. Sci. U. S. A.* **107**, 8035–40 (2010).

275. Weinzettel, J., Vačkář, D. & Medková, H. Human footprint in biodiversity hotspots. *Front. Ecol. Environ.* **16**, 447–452 (2018).

276. Pfister, S., Bayer, P., Koehler, A. & Hellweg, S. Environmental Impacts of Water Use in Global Crop Production: Hotspots and Trade-Offs with Land Use. *Environ. Sci. Technol.* **45**, 5761–5768 (2011).

277. Obersteiner, M. *et al.* Assessing the land resource–food price nexus of the Sustainable Development Goals. *Sci. Adv.* **2**, e1501499 (2016).

278. Isbell, F. *et al.* Linking the influence and dependence of people on biodiversity across scales. *Nature* **546**, 65–72 (2017).

279. Díaz, S. *et al.* Assessing nature's contributions to people. *Science (80-.).* **359**, 270 LP-272 (2018).

280. Rockström, J. *et al.* A safe operating space for humanity. *Nature* **461**, 472–475 (2009).

281. Steffen, W. *et al.* Planetary boundaries: Guiding human development on a changing planet. *Science (80-.).* **347**, 1259855 (2015).

282. Samper, C. Planetary boundaries: Rethinking biodiversity. *Nat. Clim. Chang.* **1**, 118–119 (2009).

283. UN. Transforming our world: The 2030 agenda for sustainable development. *Resolut. Adopt. by Gen. Assem.* (2015).

284. CBD High-Level Panel. *Resourcing the Aichi Biodiversity Targets: An Assessment of Benefits, Investments and Resource needs for Implementing the Strategic Plan for Biodiversity 2011-2020.* (2014).

285. KBA Standards and Appeals Committee. *Guidelines for using a global standard for the identification of Key Biodiversity Areas : version 1.0.* (2019) doi:10.2305/IUCN.CH.2019.KBA.1.0.en.

286. BirdLife International. *Digital boundaries of Key Biodiversity Areas from the World Database of Key Biodiversity Areas.*

http://www.keybiodiversityareas.org/site/requestgis (2020).

287. Langhammer, P. F. *et al*. *Identification and Gap Analysis of Key Biodiversity Areas: Targets for Comprehensive Protected Area Systems*. (2007).

288. Convention on Biological Diversity. *Updated synthesis of the proposals of Parties and observers on the structure of the post-2020 global biodiversity framework and its targets*. (2020) doi:https://www.cbd.int/conferences/post2020/post2020-prep-01/documents.

289. Visconti, P. *et al.* Protected area targets post-2020. *Science (80-.).* **364**, 239 LP-241 (2019).

290. Dudley, N., Boucher, J. L., Cuttelod, A., Brooks, T. M. & Langhammer, P. F. *Applications of Key Biodiversity Areas: End-user consultations*. (2014).

291. Marques, A. *et al.* Increasing impacts of land use on biodiversity and carbon sequestration driven by population and economic growth. *Nat. Ecol. Evol.* **3**, 628–637 (2019).

292. Chaudhary, A. & Brooks, T. M. Land Use Intensity-Specific Global Characterization Factors to Assess Product Biodiversity Footprints. *Environ. Sci. Technol.* **52**, 5094–5104 (2018).

293. Sun, Z., Scherer, L., Tukker, A. & Behrens, P. Linking global crop and livestock consumption to local production hotspots. *Glob. Food Sec.* **25**, 100323 (2020).

294. Lenzen, M. *et al.* International trade drives biodiversity threats in developing nations. *Nature* **486**, 109–112 (2012).

295. Peters, G. P., Minx, J. C., Weber, C. L. & Edenhofer, O. Growth in emission transfers via international trade from 1990 to 2008. *Proc. Natl. Acad. Sci. U. S. A.* **108**, 8903–8908 (2011).

296. Moran, D. & Kanemoto, K. Identifying species threat hotspots from global supply chains. *Nat. Ecol. Evol.* **1**, 0023 (2017).

297. Vijay, V. & Armsworth, P. R. Pervasive cropland in protected areas highlight trade-offs between conservation and food security. *Proc. Natl. Acad. Sci. U. S. A.* **118**, (2021).

298. Green, J. M. H. *et al.* Linking global drivers of agricultural trade to on-the-ground impacts on biodiversity. *Proc. Natl. Acad. Sci. U. S. A.* **116**, 23202–23208 (2019).

299. Alkemade, R., Reid, R. S., Van Den Berg, M., De Leeuw, J. & Jeuken, M. Assessing the impacts of livestock production on biodiversity in rangeland ecosystems. *Proc. Natl. Acad. Sci. U. S. A.* **110**, 20900–20905 (2013).

300. Reid, R. *et al.* Global Livestock Impacts on Biodiversity. in *Livestock in a Changing Landscape. Drivers, Consequences, and Responses* (eds. Steinfeld, H., Mooney, H. A., Schneider, F. & Neville, L. E.) 111–138 (Island Press, 2010).

301. Jones, P. J. Biodiversity in the Gulf of Guinea: an overview. *Biodivers. Conserv.* **3**, 772–784 (1994).

302. Chaudhary, A., Verones, F., de Baan, L. & Hellweg, S. Quantifying Land Use Impacts on Biodiversity: Combining Species–Area Models and Vulnerability Indicators. *Environ. Sci. Technol.* **49**, 9987–9995 (2015).

303. Newbold, T. *et al.* Global effects of land use on local terrestrial biodiversity. *Nature* **520**, 45–50 (2015).

304. Chaudhary, A., Pfister, S. & Hellweg, S. Spatially Explicit Analysis of Biodiversity Loss Due to Global Agriculture, Pasture and Forest Land Use from a Producer and Consumer Perspective. *Environ. Sci. Technol.* **50**, 3928–3936 (2016).

305. Henry, R. C. *et al.* The role of global dietary transitions for safeguarding biodiversity. *Glob. Environ. Chang.* **58**, 101956 (2019).

306. Leclère, D. *et al.* Bending the curve of terrestrial biodiversity needs an integrated strategy. *Nature* 1–6 (2020).

307. Weinzettel, J., Vačkář, D. & Medková, H. Human footprint in biodiversity hotspots. *Front. Ecol. Environ.* **16**, 447–452 (2018).

308. Chaudhary, A. & Brooks, T. M. National Consumption and Global Trade Impacts on Biodiversity. *World Dev.* **121**, 178–187 (2019).

309. Balmford, A. *et al.* Conservation conflicts across africa. *Science (80-.).* **291**, 2616–2619 (2001).

310. Rands, M. R. W. *et al.* Biodiversity conservation: Challenges beyond 2010. *Science* vol. 329 1298–1303 (2010).

311. Kullberg, P., Di Minin, E. & Moilanen, A. Using key biodiversity areas to guide effective expansion of the global protected area network. *Glob. Ecol. Conserv.* **20**, e00768 (2019).

312. Bingham, H. C. *et al.* Sixty years of tracking conservation progress using the World Database on Protected Areas. *Nat. Ecol. Evol.* **3**, 737–743 (2019).

313. Johnson, D. M. Using the Landsat archive to map crop cover history across the United States. *Remote Sens. Environ.* **232**, 111286 (2019).

314. Descals, A. *et al.* High-resolution global map of smallholder and industrial closed-canopy oil palm plantations. *Earth Syst. Sci. Data Discuss.* (2020) doi:10.5194/essd-2020-159.

315. Fritz, S. *et al.* Mapping global cropland and field size. *Glob. Chang. Biol.* **21**, 1980–1992 (2015).

316. Marques, A., Verones, F., Kok, M. T. J., Huijbregts, M. A. J. & Pereira, H. M. How to

quantify biodiversity footprints of consumption? A review of multi-regional input–output analysis and life cycle assessment. *Curr. Opin. Environ. Sustain.* **29**, 75–81 (2017).

317. Duelli, P. & Obrist, M. K. Biodiversity indicators: the choice of values and measures. *Agric. Ecosyst. Environ.* **98**, 87–98 (2003).

318. Scherer, L., van Baren, S. A. & van Bodegom, P. M. Characterizing land use impacts on functional plant diversity for life cycle assessments. *Environ. Sci. Technol.* acs.est.9b07228 (2020) doi:10.1021/acs.est.9b07228.

319. Chiarucci, A., Bacaro, G. & Scheiner, S. M. Old and new challenges in using species diversity for assessing biodiversity. *Philos. Trans. R. Soc. B Biol. Sci.* **366**, 2426–2437 (2011).

320. Marquardt, S. G. *et al.* Consumption-based biodiversity footprints – Do different indicators yield different results? *Ecol. Indic.* **103**, 461–470 (2019).

321. Mazor, T. *et al.* Global mismatch of policy and research on drivers of biodiversity loss. *Nat. Ecol. Evol.* **2**, 1071–1074 (2018).

322. IPBES. *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. (2019) doi:https://doi.org/10.5281/zenodo.3553579.

323. Bruckner, M. *et al.* FABIO—The Construction of the Food and Agriculture Biomass Input–Output Model. *Environ. Sci. Technol.* **53**, 11302–11312 (2019).

324. Stadler, K. *et al.* EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. *J. Ind. Ecol.* **22**, 502–515 (2018).

325. Kanemoto, K., Moran, D. & Hertwich, E. G. Mapping the Carbon Footprint of Nations. *Environ. Sci. Technol.* **50**, 10512–10517 (2016).

326. Scherer, L. *et al.* Trade-offs between social and environmental Sustainable Development Goals. *Environ. Sci. Policy* **90**, 65–72 (2018).

327. Semba, R. D. *et al.* Adoption of the ‘planetary health diet’ has different impacts on countries’ greenhouse gas emissions. *Nat. Food* **1**, 481–484 (2020).

328. Behrens, P. *et al.* Evaluating the environmental impacts of dietary recommendations. *Proc. Natl. Acad. Sci. U. S. A.* **114**, 13412–13417 (2017).

329. FAOSTAT. FAOSTAT. *FAOSTAT* (2019).

330. You, L., Wood-Sichra, U., Bacou, M. & Koo, J. Spatial Production Allocation Model (SPAM) 2005 v3.2. (2017).

331. Monfreda, C., Ramankutty, N. & Foley, J. A. Farming the planet: 2. Geographic

distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochem. Cycles* **22**, n/a-n/a (2008).

332. Bruckner, M., Fischer, G., Tramberend, S. & Giljum, S. Measuring telecouplings in the global land system: A review and comparative evaluation of land footprint accounting methods. *Ecol. Econ.* **114**, 11–21 (2015).

333. Schulze, K., Malek, Ž. & Verburg, P. H. Towards better mapping of forest management patterns: A global allocation approach. *For. Ecol. Manage.* **432**, 776–785 (2019).

334. Hansen, M. C. *et al.* High-resolution global maps of 21st-century forest cover change. *Science (80-.).* **342**, 850–853 (2013).

335. Hoskins, A. J. *et al.* Downscaling land-use data to provide global 30″ estimates of five land-use classes. *Ecol. Evol.* **6**, 3040–3055 (2016).

336. Erb, K.-H. *et al.* A comprehensive global 5 min resolution land-use data set for the year 2000 consistent with national census data. *J. Land Use Sci.* **2**, 191–224 (2007).

337. Sun, Z., Tukker, A. & Behrens, P. Going Global to Local: Connecting Top-Down Accounting and Local Impacts, A Methodological Review of Spatially Explicit Input–Output Approaches. *Environ. Sci. Technol.* **53**, 1048–1062 (2019).

338. Martins, I. S. & Pereira, H. M. Improving extinction projections across scales and habitats using the countryside species-area relationship. *Sci. Rep.* **7**, 1–7 (2017).

339. Chaudhary, A., Verones, F., De Baan, L., Pfister, S. & Hellweg, S. *Land stress: Potential species loss from land use (global; PSSRg)*. (2016).

340. Clark, M. A. *et al.* Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. *Science (80-.).* **370**, 705–708 (2020).

341. Griscom, B. W. *et al.* Natural climate solutions. *Proc. Natl. Acad. Sci. U. S. A.* **114**, 11645–11650 (2017).

342. Willett, W. *et al.* Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet* vol. 393 447–492 (2019).

343. Searchinger, T., Waite, R., Hanson, C. & Ranganathan, J. *Creating a sustainable food future: a menu of solutions to feed nearly 10 billion people by 2050. World Resources Institute* vol. 1 (2019).

344. Canadell, J. G. & Schulze, E. D. Global potential of biospheric carbon management for climate mitigation. *Nat. Commun.* **5**, 1–12 (2014).

345. Herrero, M. *et al.* Greenhouse gas mitigation potentials in the livestock sector. *Nature Climate Change* vol. 6 452–461 (2016).

346. Meier, T. & Christen, O. Environmental impacts of dietary recommendations and dietary

styles: Germany as an example. *Environ. Sci. Technol.* **47**, 877–888 (2013).

347. Westhoek, H. *et al.* Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. *Glob. Environ. Chang.* **26**, 196–205 (2014).

348. Sahlin, K. R., Röös, E. & Gordon, L. J. 'Less but better'meat is a sustainability message in need of clarity. *Nat. Food* **1**, 520–522 (2020).

349. Behrens, P. *et al.* Evaluating the environmental impacts of dietary recommendations. *Proc. Natl. Acad. Sci. U. S. A.* **114**, 13412–13417 (2017).

350. Fargione, J. E. *et al.* Natural climate solutions for the United States. *Sci. Adv.* **4**, eaat1869 (2018).

351. Lamb, A. *et al.* The potential for land sparing to offset greenhouse gas emissions from agriculture. *Nat. Clim. Chang.* **6**, 488–492 (2016).

352. Erb, K. H. *et al.* Unexpectedly large impact of forest management and grazing on global vegetation biomass. *Nature* **553**, 73–76 (2018).

353. Searchinger, T. D., Wirsenius, S., Beringer, T. & Dumas, P. Assessing the efficiency of changes in land use for mitigating climate change. *Nature* vol. 564 249–253 (2018).

354. Cook-Patton, S. C. *et al.* Mapping carbon accumulation potential from global natural forest regrowth. *Nature* **585**, 545–550 (2020).

355. Soto-Navarro, C. *et al.* Mapping co-benefits for carbon storage and biodiversity to inform conservation policy and action. *Philos. Trans. R. Soc. B Biol. Sci.* **375**, 20190128 (2020).

356. Sanderman, J., Hengl, T. & Fiske, G. J. Soil carbon debt of 12,000 years of human land use. *Proc. Natl. Acad. Sci. U. S. A.* **114**, 9575–9580 (2017).

357. FAO. FAOSTAT. (2020).

358. Spawn, S. A., Sullivan, C. C., Lark, T. J. & Gibbs, H. K. Harmonized global maps of above and belowground biomass carbon density in the year 2010. *Sci. Data* **7**, (2020).

359. Hengl, T. & Wheeler, I. Soil organic carbon stock in kg/m2 for 5 standard depth intervals (0–10, 10–30, 30–60, 60–100 and 100–200 cm) at 250 m resolution. (2018) doi:10.5281/ZENODO.2536040.

360. Sun, Z., Scherer, L., Tukker, A. & Behrens, P. Linking global crop and livestock consumption to local production hotspots. *Glob. Food Sec.* **25**, 100323 (2019).

361. Kanemoto, K., Moran, D. & Hertwich, E. G. Mapping the Carbon Footprint of Nations. *Environ. Sci. Technol.* **50**, 10512–10517 (2016).

362. Hayek, M. N., Harwatt, H., Ripple, W. J. & Mueller, N. D. The carbon opportunity cost

of animal-sourced food production on land. *Nat. Sustain.* 1–4 (2020) doi:10.1038/s41893-020-00603-4.

363. De Vrese, M. *et al.* Probiotics - Compensation for lactase insufficiency. in *American Journal of Clinical Nutrition* vol. 73 421s–429s (American Society for Nutrition, 2001).

364. Scherer, L., Behrens, P. & Tukker, A. Opportunity for a Dietary Win-Win-Win in Nutrition, Environment, and Animal Welfare. *One Earth* **1**, 349–360 (2019).

365. Shepon, A., Eshel, G., Noor, E. & Milo, R. The opportunity cost of animal based diets exceeds all food losses. *Proc. Natl. Acad. Sci. U. S. A.* **115**, 3804–3809 (2018).

366. Laroche, P. C. S. J., Schulp, C. J. E., Kastner, T. & Verburg, P. H. Telecoupled environmental impacts of current and alternative Western diets. *Glob. Environ. Chang.* **62**, 102066 (2020).

367. Scherer, L. A., Verburg, P. H. & Schulp, C. J. E. Opportunities for sustainable intensification in European agriculture. *Glob. Environ. Chang.* **48**, 43–55 (2018).

368. Lire Wachamo, H. Review on Health Benefit and Risk of Coffee Consumption. *Med. Aromat. Plants* **6**, (2017).

369. Zaitsu, M., Takeuchi, T., Kobayashi, Y. & Kawachi, I. Light to moderate amount of lifetime alcohol consumption and risk of cancer in Japan. *Cancer* **126**, 1031–1040 (2020).

370. Osorio-Paz, I., Brunauer, R. & Alavez, S. Beer and its non-alcoholic compounds in health and disease. *Critical Reviews in Food Science and Nutrition* (2019) doi:10.1080/10408398.2019.1696278.

371. de Coninck, P. & Gilmore, I. Long overdue: a fresh start for EU policy on alcohol and health. *The Lancet* vol. 395 10–13 (2020).

372. Manthey, J. *et al.* Global alcohol exposure between 1990 and 2017 and forecasts until 2030: a modelling study. *Lancet* **393**, 2493–2502 (2019).

373. Bansback, B. Future Directions for the Global Meat Industry? *EuroChoices* **13**, 4–11 (2014).

374. Xue, L. *et al.* Efficiency and Carbon Footprint of the German Meat Supply Chain. *Environ. Sci. Technol.* **53**, 5133–5142 (2019).

375. IPCC. *Global warming of 1.5°C*. (2018) doi:https://www.ipcc.ch/sr15/.

376. Pozo, C., Galán-Martín, Á., Reiner, D. M., Mac Dowell, N. & Guillén-Gosálbez, G. Equity in allocating carbon dioxide removal quotas. *Nat. Clim. Chang.* **10**, 640–646 (2020).

377. Folberth, C. *et al.* The global cropland-sparing potential of high-yield farming. *Nat. Sustain.* **3**, 281–289 (2020).

378. Goldstein, A. *et al.* Protecting irrecoverable carbon in Earth's ecosystems. *Nat. Clim. Chang.* 1–9 (2020).

379. Yang, Y. *et al.* Restoring Abandoned Farmland to Mitigate Climate Change on a Full Earth. *One Earth* **3**, 176–186 (2020).

380. Yang, Y., Tilman, D., Furey, G. & Lehman, C. Soil carbon sequestration accelerated by restoration of grassland biodiversity. *Nat. Commun.* **10**, 1–7 (2019).

381. Lewis, S. L., Wheeler, C. E., Mitchard, E. T. A. & Koch, A. Restoring natural forests is the best way to remove atmospheric carbon. *Nature* **568**, 25–28 (2019).

382. van Zalk, J. & Behrens, P. The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S. *Energy Policy* **123**, 83–91 (2018).

383. Field, J. L. *et al.* Robust paths to net greenhouse gas mitigation and negative emissions via advanced biofuels. *Proc. Natl. Acad. Sci. U. S. A.* **117**, 21968–21977 (2020).

384. Tilman, D., Hill, J. & Lehman, C. Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science (80-.).* **314**, 1598–1600 (2006).

385. Robertson, G. P. *et al.* Cellulosic biofuel contributions to a sustainable energy future: Choices and outcomes. *Science* vol. 356 (2017).

386. Philipso, C. D. *et al.* Active restoration accelerates the carbon recovery of human-modified tropical forests. *Science (80-.).* **369**, 838–841 (2020).

387. Zahawi, R. A., Reid, J. L. & Holl, K. D. Hidden Costs of Passive Restoration. *Restor. Ecol.* **22**, 284–287 (2014).

388. Scown, M. W., Brady, M. V. & Nicholas, K. A. Billions in Misspent EU Agricultural Subsidies Could Support the Sustainable Development Goals. *One Earth* **3**, 237–250 (2020).

389. The Food and Land Use Coalition. *Growing Better: Ten Critical Transitions to Transform Food and Land Use*. (2019).

390. International Food Policy Research Institute (IFPRI). Global Spatially-Disaggregated Crop Production Statistics Data for 2010 Version 1.1. *Harvard Dataverse, V3* (2019) doi:https://doi.org/10.7910/DVN/PRFF8V.

391. Wolf, J. *et al.* Biogenic carbon fluxes from global agricultural production and consumption. *Global Biogeochem. Cycles* **29**, 1617–1639 (2015).

392. Lal, R. Digging deeper: A holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems. *Global Change Biology* vol. 24 3285–3301 (2018).

393. Sloat, L. L. *et al.* Increasing importance of precipitation variability on global livestock

grazing lands. *Nat. Clim. Chang.* **8**, 214–218 (2018).

394. West, P. C. *et al.* Trading carbon for food: Global comparison of carbon stocks vs. crop yields on agricultural land. *Proc. Natl. Acad. Sci. U. S. A.* **107**, 19645–19648 (2010).

395. Johnson, J. A., Runge, C. F., Senauer, B., Foley, J. & Polasky, S. Global agriculture and carbon trade-offs. *Proc. Natl. Acad. Sci. U. S. A.* **111**, 12342–12347 (2014).

396. Beck, H. E. *et al.* Present and future köppen-geiger climate classification maps at 1-km resolution. *Sci. Data* **5**, 1–12 (2018).

397. Hirvonen, K., Bai, Y., Headey, D. & Masters, W. A. Affordability of the EAT–Lancet reference diet: a global analysis. *Lancet Glob. Heal.* **8**, e59–e66 (2020).

398. Hanley-Cook, G. T. *et al.* EAT- Lancet Diet Score Requires Minimum Intake Values to Predict Higher Micronutrient Adequacy of Diets in Rural Women of Reproductive Age from Five Low- And Middle-Income Countries. *Br. J. Nutr.* 1–9 (2020) doi:10.1017/S0007114520003864.

399. Xie, W. *et al.* Decreases in global beer supply due to extreme drought and heat. *Nat. Plants* **4**, 964–973 (2018).

400. Hasegawa, T. *et al.* Risk of increased food insecurity under stringent global climate change mitigation policy. *Nat. Clim. Chang.* **8**, 699–703 (2018).

401. Griffiths, P., Nendel, C. & Hostert, P. Intra-annual reflectance composites from Sentinel-2 and Landsat for national-scale crop and land cover mapping. *Remote Sens. Environ.* **220**, 135–151 (2019).

402. Wang, J. *et al.* Mapping sugarcane plantation dynamics in Guangxi, China, by time series Sentinel-1, Sentinel-2 and Landsat images. *Remote Sens. Environ.* **247**, 111951 (2020).

403. Massey, R. *et al.* MODIS phenology-derived, multi-year distribution of conterminous U.S. crop types. *Remote Sens. Environ.* **198**, 490–503 (2017).

404. Azzari, G., Jain, M. & Lobell, D. B. Towards fine resolution global maps of crop yields: Testing multiple methods and satellites in three countries. *Remote Sens. Environ.* **202**, 129–141 (2017).

405. Lu, M. *et al.* A cultivated planet in 2010 – Part 1: The global synergy cropland map. *Earth Syst. Sci. Data* **12**, 1913–1928 (2020).

406. Descals, A. *et al.* High-resolution global map of smallholder and industrial closed-canopy oil palm plantations. *Earth Syst. Sci. Data Discuss.* 1–22 (2020) doi:10.5194/essd-2020-159.

407. Zhou, Y. *et al.* Sharing tableware reduces waste generation, emissions and water consumption in China's takeaway packaging waste dilemma. *Nat. Food* **1**, 552–561 (2020).

408. Chu, J., Liu, H. & Salvo, A. Air pollution as a determinant of food delivery and related plastic waste. *Nat. Hum. Behav.* **5**, 212–220 (2020).

409. Carvalho, V. M. *et al.* Tracking the COVID-19 crisis with high-resolution transaction data. (2020).

410. Dong, L., Ratti, C. & Zheng, S. Predicting neighborhoods' socioeconomic attributes using restaurant data. *Proc. Natl. Acad. Sci. U. S. A.* **116**, 15447–15452 (2019).

411. Kang, P. *et al.* Low-carbon pathways for the booming express delivery sector in China. *Nat. Commun.* **12**, 1–8 (2021).

412. Goldstein, B., Gounaridis, D. & Newell, J. P. The carbon footprint of household energy use in the United States. *Proc. Natl. Acad. Sci. U. S. A.* **117**, 19122–19130 (2020).

413. Liebe, U., Gewinner, J. & Diekmann, A. Large and persistent effects of green energy defaults in the household and business sectors. *Nat. Hum. Behav.* 1–10 (2021) doi:10.1038/s41562-021-01070-3.

414. Bjelle, E. L. *et al.* Adding country resolution to EXIOBASE: impacts on land use embodied in trade. *J. Econ. Struct.* **9**, 14 (2020).

415. Lenzen, M. *et al.* The Global MRIO Lab–charting the world economy. *Econ. Syst. Res.* **29**, 158–186 (2017).

416. Jiang, M. *et al.* Improving Subnational Input-Output Analyses Using Regional Trade Data: A Case-Study and Comparison. *Environ. Sci. Technol.* **54**, 12732–12741 (2020).

417. OEC. The Observatory of Economic Complexity. *OEC* https://oec.world/ (2021).

418. Barbier, E. B., Burgess, J. C. & Dean, T. J. How to pay for saving biodiversity. *Science (80-.).* **360**, 486 LP-488 (2018).

419. Vijay, V. & Armsworth, P. R. Pervasive cropland in protected areas highlight trade-offs between conservation and food security. *Proc. Natl. Acad. Sci. U. S. A.* **118**, 2021 (2021).

420. Vollset, S. E. *et al.* Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: a forecasting analysis for the Global Burden of Disease Study. *Lancet* (2020) doi:10.1016/S0140-6736(20)30677-2.

421. Bager, S. L., Persson, U. M. & dos Reis, T. N. P. Eighty-six EU policy options for reducing imported deforestation. *One Earth* **4**, 289–306 (2021).

422. Dallimer, M. & Strange, N. Why socio-political borders and boundaries matter in conservation. *Trends in Ecology and Evolution* vol. 30 132–139 (2015).

423. Wilman, E. A. Market Redirection Leakage in the Palm Oil Market. *Ecol. Econ.* **159**, 226–234 (2019).

424. Moher, D. *et al.* Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. *Syst. Rev.* **4**, 1 (2015).

425. Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G. & Group, P. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS Med.* **6**, e1000097 (2009).

426. Didan, K. MOD13Q1 MODIS/Terra Vegetation Indices 16-Day L3 Global 250m SIN Grid V006. NASA EOSDIS Land Processes DAAC. *USGS* vol. 5 2002–2015 (2015).

427. European Space Agency. 300 m Annual global land cover time series from 1992 to 2015. *Eur. Sp. Agency - Clim. Chang. Initiat.* (2017).

428. Heffer, P. *Assessment of Fertilizer Use by Crop at the Global Level*. (2013).

429. Scherer, L. & Verburg, P. H. Mapping and linking supply- and demand-side measures in climate-smart agriculture. A review. *Agronomy for Sustainable Development* vol. 37 1–17 (2017).

430. Sakiroglu, M., Dong, C., Hall, M. B., Jungers, J. & Picasso, V. How does nitrogen and forage harvest affect belowground biomass and nonstructural carbohydrates in dual-use Kernza intermediate wheatgrass? *Crop Sci.* **60**, 2562–2573 (2020).

431. Lanker, M., Bell, M. & Picasso, V. D. Farmer perspectives and experiences introducing the novel perennial grain Kernza intermediate wheatgrass in the US Midwest. *Renew. Agric. Food Syst.* 1–10 (2019) doi:10.1017/S1742170519000310.

432. Hristov, A. N. *et al.* An inhibitor persistently decreased enteric methane emission from dairy cows with no negative effect on milk production. *Proc. Natl. Acad. Sci. U. S. A.* **112**, 10663–10668 (2015).

433. EURL. *Evaluation Report on the Analytical Methods submitted in connection with the Application for Authorisation of a Feed Additive according to Regulation (EC) No 1831/2003 3-Nitrooxypropanol (preparation of minimum of 10 % of 3-nitrooxypropanol)*. (2020).

434. Popkin, B. M., Corvalan, C. & Grummer-Strawn, L. M. Dynamics of the double burden of malnutrition and the changing nutrition reality. *The Lancet* vol. 395 65–74 (2020).

435. Xue, L. *et al.* Missing Food, Missing Data? A Critical Review of Global Food Losses and Food Waste Data. *Environ. Sci. Technol.* **51**, 6618–6633 (2017).

436. Yu, Y. & Jaenicke, E. C. Estimating Food Waste as Household Production Inefficiency. *Am. J. Agric. Econ.* **102**, 525–547 (2020).

437. Roe, S. *et al.* Contribution of the land sector to a 1.5 °C world. *Nature Climate Change* vol. 9 817–828 (2019).

438. Reganold, J. P. & Wachter, J. M. Organic agriculture in the twenty-first century. *Nature*

plants vol. 2 15221 (2016).

439. Knapp, S. & van der Heijden, M. G. A. A global meta-analysis of yield stability in organic and conservation agriculture. *Nat. Commun.* **9**, 1–9 (2018).

Appendix

8 Appendix

8.1 Supporting information to chapter 2

8.1.1 Critical review methodology – selection of the literature

We searched all papers using spatially-explicit input-output (SIO) approaches published before March, 2018 and analyzed their spatial scale, method, and environmental impacts.

We use Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to search for articles using SIO approaches, on March, 2018 (Figure S 8.1) [424]. PRISMA aims to be a standard operating procedure for systematic reviews, in order give a more reliable and less biased result [425]. The systematic and explicit methods for this systematic review reduces issues with identifying, selecting, synthesizing, summarizing, collecting and analyzing data [425]. It also allows for reproducibility by providing all the information required to perform the review. We searched three scientific catalogues: Web of Science, ScienceDirect and the Leiden University Catalogue. There is a large diversity of terms in the literature describing the same, spatially-explicit concept, including “map”, “mapping”, and “hotspots”. Of course, not all of these are synonyms, and not all of these studies are in fact spatially-explicit. In order to restrict the search further we included terms including “input-output” and “MRIO (Multi-Regional Input Output)”, For example, we use the combination of (“spatial*” or “map*” or “hotspot*”) and ("input output analysis" or "input output model" or "input output table" or "MRIO") in for the research topic in Web of Science. For the detailed protocol please see the Supporting Information.

The search criteria are: (1) that all papers are in English; (2) that all papers are in peer-reviewed; (3) that all papers use input-output method; (4) that all papers have spatially distributed results at a resolution higher than regional. A flow diagram of the search methodology is shown in Table S 8.1. After using search protocols, we find another 15 papers using Google Scholar, and then perform a snowball sampling of these papers, finding a further 14 eligible papers.

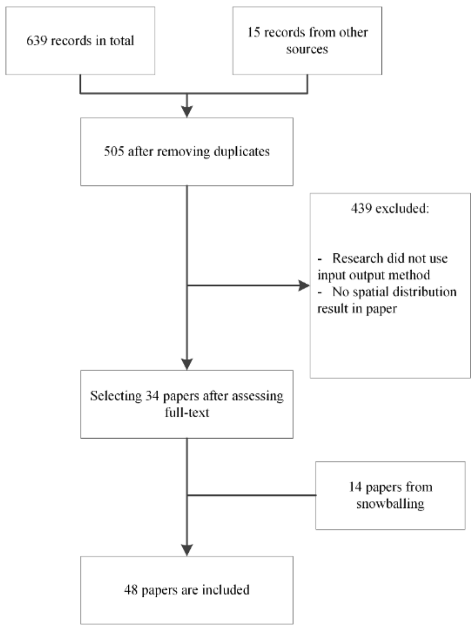

Figure S 8.1 Flow diagram of the search methodology used. After a large number of initial studies were found, these were filtered on the criteria described above to 48 analyses.

All these search terms are based on snowball sampling for each search library. Details are in Table S 8.1

Table S 8.1 Search terms used in meta-analysis for each database.

Database	Code	Search Results	After Duplicates Removed	Titles and Abstracts Screened				
Web of Science	(TS=("spatial*" OR "map*" OR "hotspot*") AND TS=("input output analysis" OR "input output model" OR "input output table" OR "MRIO")) *AND* LANGUAGE:(English)*AND* DOCUMENT TYPES:(Article OR Book OR Book Chapter OR Data Paper OR Database Review)	243	168	28				
ScienceDirect	(tak("input output analysis" OR "input output model" OR "input output table" or "MRIO")) AND (tak("spatial*" OR "map*" OR "hotspot*"))	155	110	16				
Leiden University Catalogue	(Any("input output analysis" OR "input output model" OR "input output table" OR "MRIO")) AND (Title("spatial*" OR "hotspot" OR "map*" OR "spatially-explicit")) AND Language(Englsih)	241	227	22	Full-text Assessed for Eligibility	Derived from other References	Derived from snowballing	Total
Total		639	505	66	19	15	14	48

8.1.2 **Methodological approaches in the literature**

Method 1: mapping between MRIO model and hydrological model—WaterGAP

Lutter et al. and Holland et al. combined an MRIO model (EXIOBASE in the case of Lutter et al. and GTAP8 in the case of Holland et al.), with WaterGAP model to research fresh water consumption embodied in trade almost at the same time [50,113]. Their core work is to build up mapping relationship between MRIO table and water consumption data from WaterGAP model by production sector, particularly different agricultural sectors (Table S 8.2).The difference was that Lutter et al mapped MRIO data into watershed scale, but Holland et al. mapped MRIO data into original resolution—0.5°×0.5° grid cell—of WaterGAP [113].

Table S 8.2 Example of disaggregation matrix, indicating which share of water consumption in a specific industry-region combination is originating form which watershed.

	Region 1			…	Region n		
	Ind 1	…	Ind n	…	Ind 1	…	Ind n
Watershed 1	0	…	0.95	…	0.57		0.3
…	…	…	…	…	…	…	…
Watershed m	1	…	0.05	…	0.43	…	0.7

Source: from Lutter et al.[50]

Method 2: identifying hotspots from supply chains

Kanemoto et al. developed a spatially-explicit MRIO method to identify spatially-explicit environmental impacts hotspots embodied in supply chain [95]. The core of this method is to nest spatial distribution map (R) into traditional multi-regional input-output model.

$$H_{(m)s} = \sum_r R^r \frac{\sum_i f_i^r \sum_{jt\neq s} L_{ij}^{rt} y_j^{ts}}{\sum_i d_i^r} \quad \text{(S1)}$$

$$H^{(c)s} = \sum_r R^r \frac{\sum_i f_i^r \sum_{jt} L_{ij}^{rt} y_j^{ts}}{\sum_i d_i^r} \quad \text{(S2)}$$

Table S 8.3 Variables and description of hotspots method.

Variables	Description
$H_{(m)s}$	the $PM_{2.5}$ emission hotspots H driven by imports (m) into country s
$H^{(c)s}$	the $PM_{2.5}$ emission hotspots H driven by total consumption (c) into country s
R	$PM_{2.5}$ emission maps term (R) are in absolute values
d	total emissions
f	intensity of $PM_{2.5}$

L	Leontief inverse
y	final demand
i	sector of origin and destination
j	sector of destination
r	exporting country
s	importing country
t	country of last sale in the consumption and imports terms

Method 3: integrating process-based model with input-output model

Wang et al. developed hybrid method that integrated process-based model with input-output model to analyze global water scarcity at basin level [97]. The most pivotal part of this method is

$$WSI_i^{BAU} = \frac{WW_i^{BAU}}{BA_i} \tag{S3}$$

$$WSI_i^{NT} = \frac{WW_i^{NT}}{BA_i} \tag{S4}$$

Table S 8.4 Variables and description of integrating process-based model with input-output model.

Variables	Description
WSI_i^{BAU}	Water stress index with international trade at basin ***i***
WSI_i^{NT}	Water stress index without international trade at basin ***i***
WW_i^{BAU}	Water withdraw at basin ***i*** with international trade
WW_i^{NT}	Water withdraw at basin ***i*** without international trade
BA_i	Blue water availability annually at basin ***i***

WW_i^{BAU} was calculated by downscaling production-based national water withdraws into basins based on water withdraw estimated Aqueduct Global Maps in 2010.

WW_i^{NT} was calculated by downscaling consumption-based national water withdraws, which got from MRIO model, into basins based on the same proportion of WW_i^{BAU}

Method 4: Integrating MRIO model with production-side location information.

Cazcarro et al. integrated input-output model with spatial location information to downscale grey water footprints into business level [116]. There were three steps to downscaling grey water footprints as following figure (Figure S 8.2): (1) estimating direct intensities of grey water footprints; (2) calculating grey water footprints with multi-regional input-output model; (3) downscaling grey water footprints into business level.

Mekonnen et al. estimated global agricultural grey water footprints driven by EU27 consumption with similar method of agricultural part in Cazcarro et al [115].

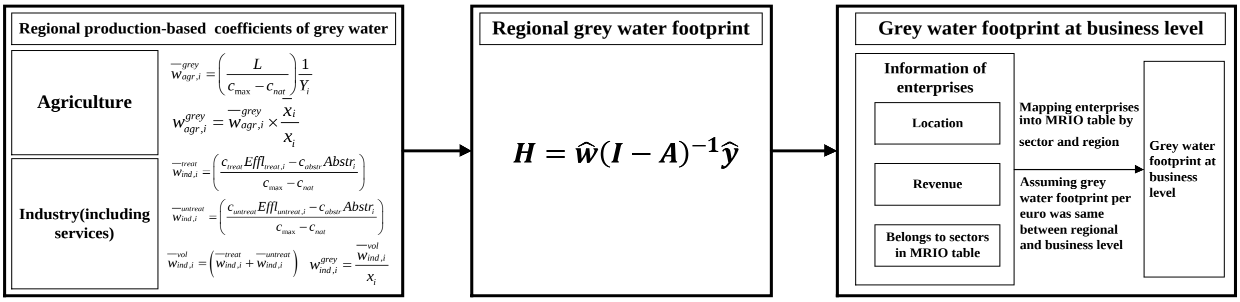

Figure S 8.2 Process of downscaling grey water footprints into business level.

Table S 8.5 Variables and description of method that downscales grey water footprints.

Variables	Description
$\overline{w}_{agr,i}^{grey}$	Agricultural physical grey water coefficient (m^3/ton) for i^{th} crop
L	Excess of nitrogen (kg/ha per year)
c_{max}	Maximum acceptable concentration
c_{nat}	Natural concentration
Y_i	Crop yield for i^{th} crop
$w_{agr,i}^{grey}$	Agricultural direct grey water coefficient (m^3/euro) for i^{th} crop
x_i	Agricultural output (euro) for i^{th} crop
$\bar{x}_i$	Agricultural production (ton) for i^{th} crop
$\overline{w}_{ind,i}^{treat}$	Amount of grey water from treated water(m^3) for sector i
$\overline{w}_{ind,i}^{untreat}$	Amount of grey water from untreated water(m^3) for sector i
c_{treat}	Concentration of treated effluent(mg/l)
c_{abstr}	Actual concentration(mg/l)
$Effl_{treat,i}$	Volume of treated effluent for sector i
$Abstr_i$	Water volume(m^3) for sector i
$c_{untreat}$	Concentration of untreated effluent(mg/l)
$Effl_{untreat,i}$	Volume of untreated effluent for sector i
$\overline{w}_{ind,i}^{vol}$	Total amount of grey water(m^3) for sector i

$w_{ind,i}^{grey}$	Direct grey water coefficient for sector *i*
$\boldsymbol{H}$	Grey water footprint matrix
$\hat{\boldsymbol{w}}$	Grey water coefficient matrix
$\boldsymbol{I}$	Identify matrix
$\boldsymbol{A}$	Technical coefficient matrix for input-output table
$\hat{\boldsymbol{y}}$	Final demand vector

Method 5: dynamic inoperability input-output model (DIIM)

Inoperability input-output model is a good tool to assess risk, and McDonald et al. integrated dynamic inoperability input-output model with volcanic locations to estimate economic loss [117].

Four steps to construct spatial map of risk by DIIM:

- splitting regional output into the finest spatial scale;
- evaluating production inoperability in each finest spatial location;
- estimating total economic impact by DIIM;
- adjusting total economic impacts based on hazard probability.

Method 6: combining data from MRIO table and demand-side subnational information.

Several researchers linked subnational information with input-output model to estimate subnational environmental impacts, the details referenced to their papers [105,108,123,126–128]. Maybe some small difference existed in their method, but the core of their method is to combine supply chain information in national input-output database or multi-regional input output database to track upstream environmental impacts with subnational consumption information to calculate subnational environmental impacts, for example consumer expenditure surveys (CESs), to calculate subnational environmental impacts.

For example, Feng et al. combined with geo-demographic data to calculate water footprints at subnational area. The core equations are as follows.

$$w_{Int} = e^{d^*}(I-A)^{-1}y + w_{hh} \quad \text{(S10)}$$

$$w_{Ext} = e^{i^*}(I-A)^{-1}y \quad \text{(S11)}$$

$$e^{d^*} = [e^d, 0] \quad \text{(S12)}$$

$$e^{i^*} = [0, e^i] \quad \text{(S13)}$$

$$y = \begin{bmatrix} y^d \\ y^i \end{bmatrix} \quad \text{(S14)}$$

Table S 8.6 Variables and description of method that combines with subnational information.

Variables	**Description**

w_{Int}	Water footprint from domestic consumption
w_{Ext}	Water footprint from other countries
w_{hh}	Water consumption from direct household consumption
e^d	Water consumption coefficients of domestic commodities
e^i	Water consumption coefficients of commodities from other countries
y^d	Final demand from domestic and export commodities
y^i	Final demand from other countries
$\boldsymbol{I}$	Identify matrix
$\boldsymbol{A}$	Technological coefficients matrix

A is from MRIO table at country level, and replace final demand ***y*** at regional level, it would calculate water footprint at local regional scale.

Method 7: integrating MRIO with GEOS-Chem model

Lin et al. and Zhang et al. combined multi-regional input-output model with GEOS-Chem to simulate transport of emissions [98,104]. Firstly, calculating environmental impacts (or emissions) embodied in trade at country level, and then using GEOS-Chem model to simulate the spatial distribution of environmental impacts on worldwide (Figure S 8.3). Zhang et al., also link health impacts model, Integrated Exposure-Response (IER), to simulate spatial distribution of premature death driven by consumption

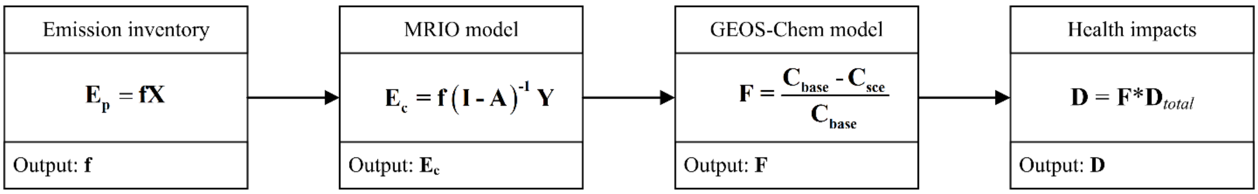

Figure S 8.3 Process of method that integrated with GEOS-Chem model.

Table S 8.7 Variables and description of method that integrated with GEOS-Chem model.

Variables	Description
$\boldsymbol{E_p}$	Emission matrix from production
$\boldsymbol{F}$	Emission intensity vector
$\boldsymbol{X}$	Total output
$\boldsymbol{E_c}$	Consumption-based emission matrix
$\boldsymbol{I}$	Identify matrix

A	Technological matrix
Y	Final demand vector
F	Spatial distribution of fractional contribution of emission derived from different scenarios
$\boldsymbol{C_{base}}$	Emission concentration on base scenarios
$\boldsymbol{C_{sce}}$	Emission concentration on different scenarios
D	Premature death population at grid cell driven by consumption
$\boldsymbol{D_{total}}$	Global total premature death population using IER model at grid cell

Method 8: combing input-output model with air pollution dispersion model.

Firstly, applying regional input-output table and emission inventory data to calculate emission coefficients of different sectors, and then using these coefficients to calculate amount of emission discharging sites [93]. Finally, applying smeared concentration approximation method (SCA) to simulate spatial diffusion of these emissions (Figure S 8.4).

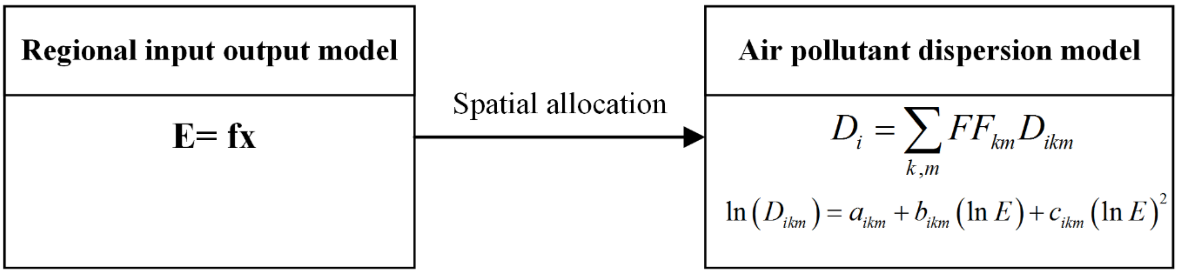

Figure S 8.4 Process of combing with air pollution dispersion model

Table S 8.8 Parameters and description of method that combines with air pollution dispersion model

Variables	Description
E	Production-based emission
F	Emission intensity
X	total output
D_i	Average concentration of emission between source and receiver
FF_{km}	Frequency of emission occur
D_{ikm}	Average contribution of concentration of emission at different situation
I	Emission classes
K	Atmospheric stability condition
M	Windspeed classes

Method 9: spatial regional econometric input–output model

Kim et al. developed spatial regional econometric input-output model through integrating regional econometric input–output model(REIM) with disequilibrium adjustment model, and they used the model to predict population and employment change of 296 municipalities in Chicago, USA [118]. The core of this method included 5 steps:

- Quantifying potential employment growth for year *t* based on exogenous national economic growth.
- Estimating information for grid cell in year *t*-1.
- Calculating employment and population at local level for year *t* based on information: (a) potential employment growth for year *t*-1 (b) information of grid cell for year *t* -1(c) their own information for year *t*-1 (d) interaction relationship between local-level employment and population.
- Updating macroeconomic variables for year *t* based on information of employment and population change with modified REIM formulation.
- Predicting information at grid cell level for year *t* via simple logic econometrics model or other more complicated simulation approach.

Method 10: Integrating MRIO model with GIS technology.

Van Der Veen et al. constructed contour map of value added based on employment data from enterprises and spatial interpolation methods with GIS platform, regarding multipliers from input-output model as the weight [121]. Similarly, Zhou et al. estimated spatial flow of chemical oxygen demand (COD) in Changzhou city, China at GIS platform [119,120,122].

Method 11 (in Trase.earth): spatially-explicit information on production to consumption systems(SEI-PCS) model

In order to trace spatial heterogeneity of environmental impacts related to production consumed by other regions within a country, especially large country, which contributes to global consumption. Godar et al. developed SEI-PCS model [109], and they used the model to analyse crops and virtual water embedded in farming commodities in Brazil at subnational scale [153,154]. The model downscales production consumed by domestic and other countries into finest scale, the municipality level, in a country. The following graph (Figure S 8.5) describes the core theory of this model, and the detail can reference to Godar et al. 2015 [109].

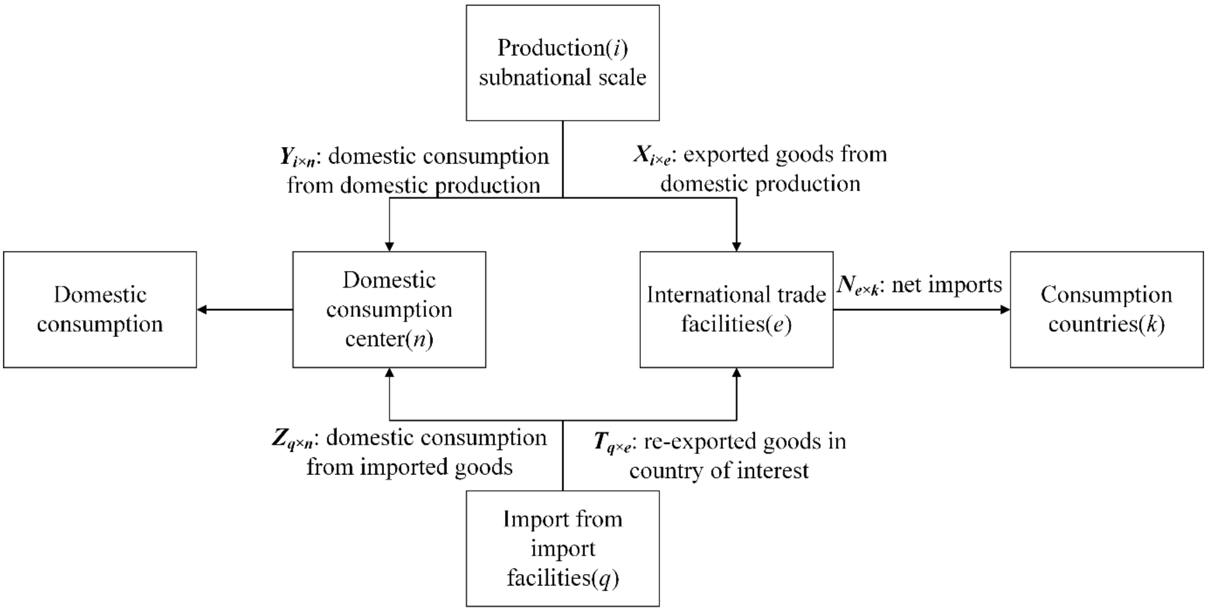

Figure S 8.5 The framework of SEI-PEC.

$$R_{i\times k} = D_{i\times e} \times L_{e\times k} \times B_{k\times k} \tag{S5}$$

$$\bar{r}_{i,k} \begin{cases} r_{i,k} & if\ k \neq country\ of\ interest \\ P_i - \sum_j r_{i,j} & if\ country = country\ of\ interst \end{cases} \tag{S6}$$

$$EI_k = EII_i \times \bar{R}_{i\times k} \tag{S7}$$

$$d_{i,e} = \frac{x_{i,e}}{\sum_i x_{i,e}} \tag{S8}$$

$$l_{e,k} = \frac{n_{e,k}}{P^k} \tag{S9}$$

Table S 8.9 Variables and description of equation in model SEI-PCS.

Variables	**description**
$R_{i\times k}$	consumption of ***k*** countries produced by ***i*** domestic producers in country of interest
$\bar{R}_{i,k}$	The revised value of $R_{i\times k}$
$D_{i\times e}$	Share of commodities from ***i*** sub-regional producers to ***e*** trade facilities
$L_{e\times k}$	Ratio between imports from countries ***k*** and production of that country
$B_{k\times k}$	Bilateral trade flow between ***k*** countries
EI_k	Environmental impacts in ***k*** countries
EII_i	Environmental impacts intensity in subnational regions ***i***
$X_{i\times e}$	Exported commodities produced in subnational regions

$\boldsymbol{Y}_{i\times n}$	Domestic production produced in subnational regions
$\boldsymbol{T}_{q\times e}$	Re-exported commodities in country of interest
$\boldsymbol{Z}_{q\times n}$	Imported commodities were consumed in country of interest
$\boldsymbol{P}^{k}$	Production of consumption countries $\boldsymbol{k}$
$\boldsymbol{x}_{i,e}$	The elements of $\boldsymbol{X}_{i\times e}$
$\boldsymbol{d}_{i,e}$	The elements of $\boldsymbol{D}_{i\times e}$
$\boldsymbol{l}_{e,k}$	The elements of $\boldsymbol{L}_{e\times k}$
$\boldsymbol{n}_{e,k}$	The elements of $\boldsymbol{N}_{e\times k}$
$\boldsymbol{r}_{i,k}$	The elements of $\boldsymbol{R}_{i\times k}$
$\bar{\boldsymbol{r}}_{i,k}$	The elements of $\bar{\boldsymbol{R}}_{i,k}$

8.2 Supporting information to chapter 3

8.2.1 Explanatory note 1

8.2.1.1 Methods for aggregating Millet and Coffee

In the SPAM databases, there are *Millet Pearl* and *Millet Small*, and *Coffee Arabica* and *Coffee Robusta*. But there are only *Millet* and *Coffee* in FAOSTAT and so EXIOBASE as well. In order to match SPAM databases with EXIOBASE, we aggregate *Millet Pearl* and *Millet Small* into *Millet*, and aggregate *Coffee Arabica* and *Coffee Robusta* into *Coffee*. Because we use total production of primary crops in SPAM, namely a value in grid cell stands for its production quantity in metric tons, we use Raster Calculator tools in ArcGIS 10.2.2 to add two raster databases of production of *Millet Pearl* and *Millet Small* as the spatial distribution of total production of *Millet*. And the similar way for calculation for *Coffee*.

8.2.1.2 Special solution for Canada

Canada is a special case for the spatial distribution of some livestock. There is no major road further north than a latitude of 70° N; yet ducks and sheep are in relative abundance north of that. Therefore, we regard the region below 70° N within a concave hull based on a 1-degree buffer around all roads as the first-priority region for export and the second-priority region for domestic consumption, and the rest as the first-priority region for second-priority region for export and the first-priority region for domestic consumption.

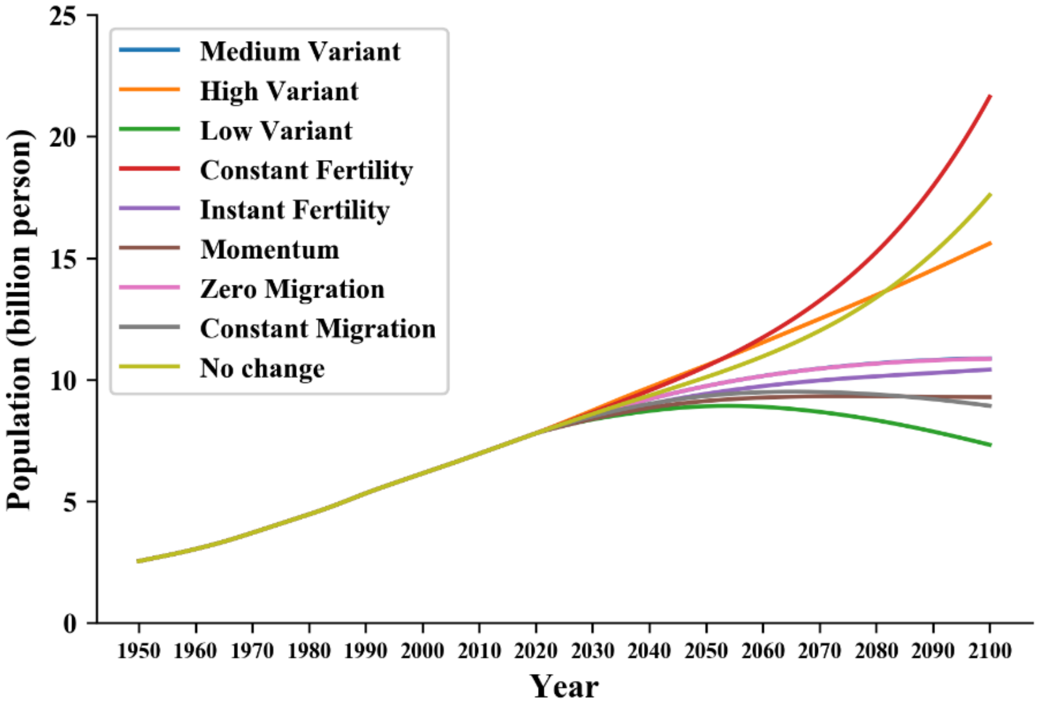

Figure S 8.6. World Population from 1950 to 2100. Source: World Population Prospects: The 2019 Revision.

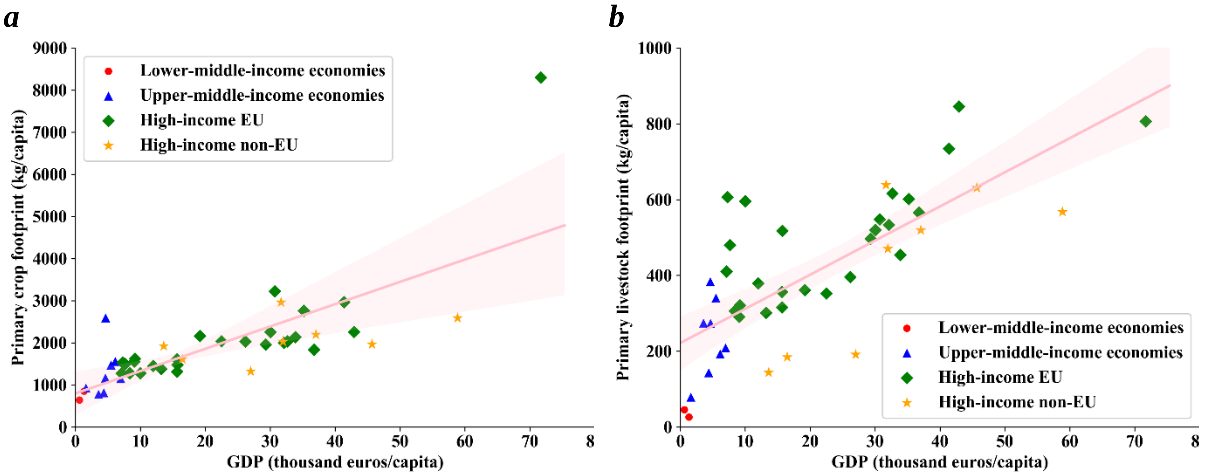

Figure S 8.7. Per-capita embodied primary crop (a) and livestock (b) consumption and per-capita GDP for 44 countries in EXIOBASE.

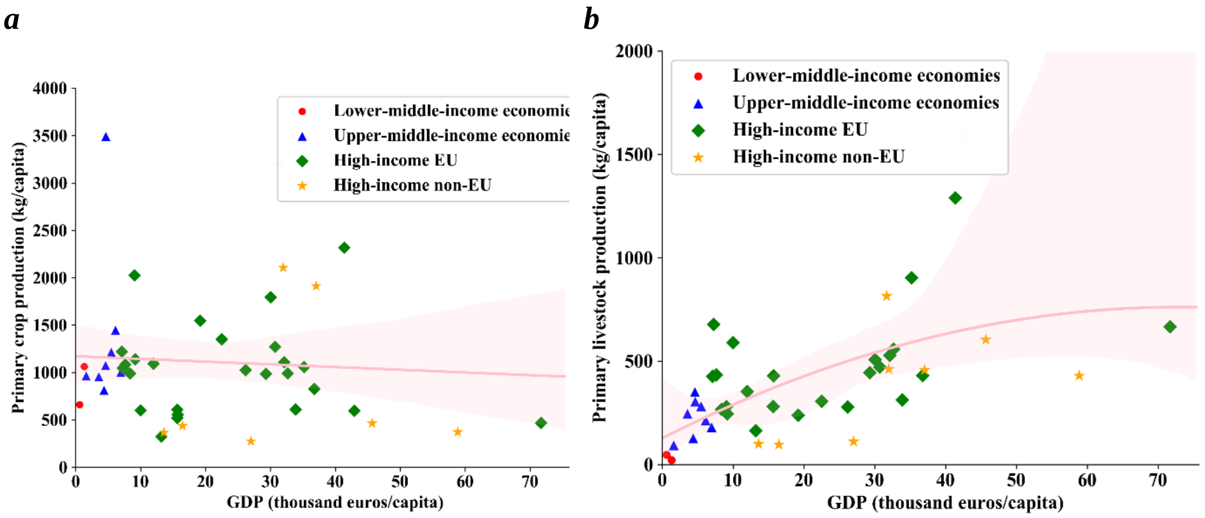

Figure S 8.8. Per-capita primary crop (a) and livestock (b) production and per-capita GDP for 44 countries in EXIOBASE.

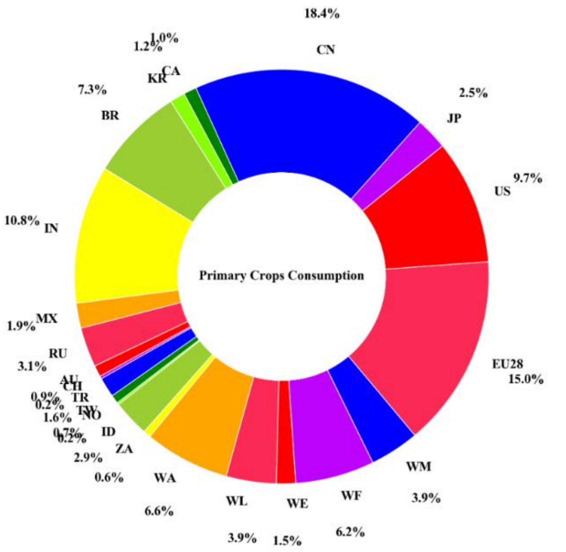

Figure S 8.9. Embodied primary crop consumption for each region in EXIOBASE

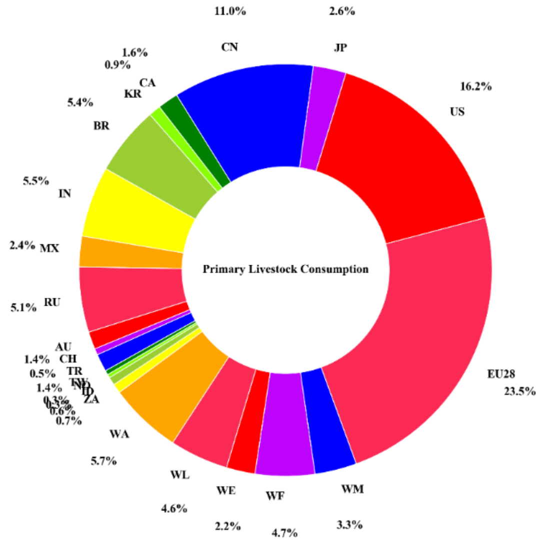

Figure S 8.10. Embodied livestock for each region in EXIOBASE

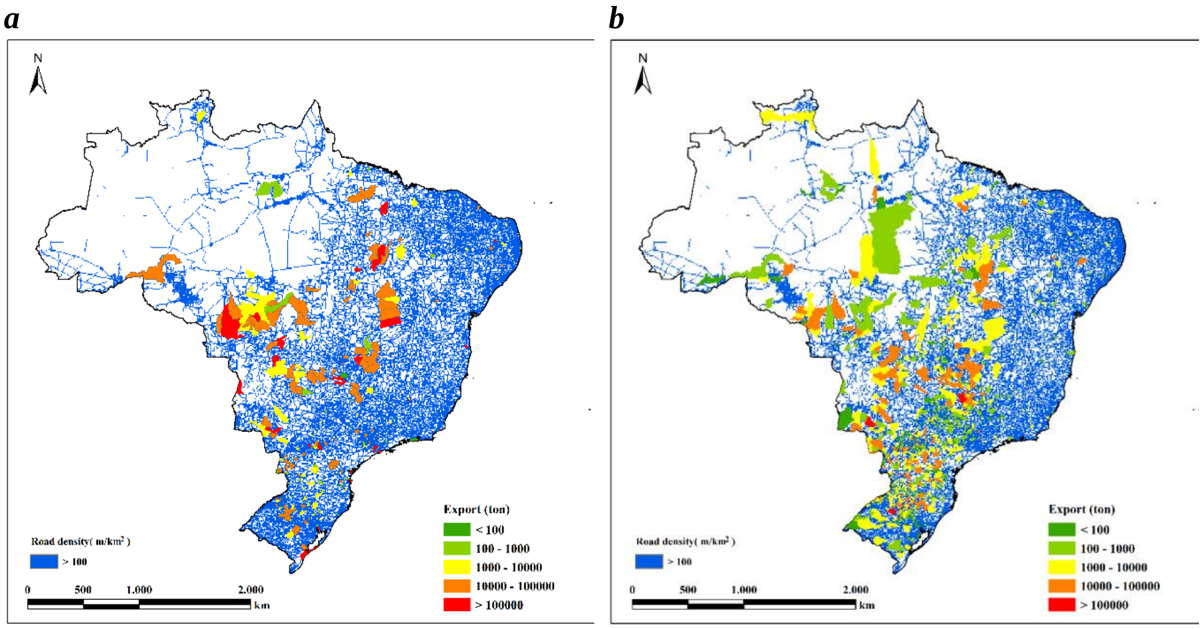

Figure S 8.11. Soybean export from official statistics data (a) and Trase.earth calculation (b) in 2006 at municipality level.

Table S 8.10. Mapping relationship between resource extensions about crop accounts in EXIOBASE with SPAM

Extensions in EXIOBASE	unit	SPAM code	name in SPAM	Sector in EXIOBASE
Domestic Extraction Used - Primary Crops – Abaca	kt	31	other fibre crops	Plant-based fibers
Domestic Extraction Used - Primary Crops - Agave Fibres nes	kt	31	other fibre crops	Plant-based fibers
Domestic Extraction Used - Primary Crops – Almonds	kt	42	rest of crops	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Anise, Badian, Fennel	kt	42	rest of crops	Crops nec
Domestic Extraction Used - Primary Crops – Apples	kt	40	temperate fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Apricots	kt	40	temperate fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Arecanuts	kt	42	rest of crops	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Artichokes	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Asparagus	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Avocados	kt	39	tropical fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Bambara beans	kt	19	other pulses	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Bananas	kt	37	banana	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Barley	kt	4	Barley	Cereal grains nec
Domestic Extraction Used - Primary Crops - Beans, dry	kt	14	Bean	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Beans, green	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Berries nec	kt	40	temperate fruit	Vegetables, fruit, nuts

Domestic Extraction Used - Primary Crops – Blueberries	kt	40	temperate fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Brazil nuts, with shell	kt	42	rest of crops	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Broad beans, horse beans, dry	kt	19	other pulses	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Buckwheat	kt	8	other cereals	Cereal grains nec
Domestic Extraction Used - Primary Crops – Cabbages	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Canary Seed	kt	8	other cereals	Cereal grains nec
Domestic Extraction Used - Primary Crops – Carobs	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Carrots	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Cashew nuts, with shell	kt	42	rest of crops	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Cashewapple	kt	39	tropical fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Cassava	kt	12	cassava	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Cassava leaves	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Castor oil seed	kt	27	other oil crops	Oil seeds
Domestic Extraction Used - Primary Crops – Cauliflower	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Cereals nec	kt	8	other cereals	Cereal grains nec
Domestic Extraction Used - Primary Crops – Cherries	kt	40	temperate fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Chestnuts	kt	42	rest of crops	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Chick peas	kt	15	chickpea	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Chicory Roots	kt	41	vegetables	Vegetables, fruit, nuts

Domestic Extraction Used - Primary Crops - Chillies and peppers, dry	kt	42	rest of crops	Crops nec
Domestic Extraction Used - Primary Crops - Chillies and peppers, green	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Cinnamon	kt	42	rest of crops	Crops nec
Domestic Extraction Used - Primary Crops - Citrus Fruit nec	kt	39	tropical fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Cloves	kt	42	rest of crops	Crops nec
Domestic Extraction Used - Primary Crops - Cocoa Beans	kt	34	Cocoa	Crops nec
Domestic Extraction Used - Primary Crops – Coconuts	kt	22	coconut	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Coffee, Green	kt	32	arabica coffee	Crops nec
Domestic Extraction Used - Primary Crops – Coir	kt	31	other fibre crops	Plant-based fibers
Domestic Extraction Used - Primary Crops - Cotton Lint	kt	30	Cotton	Plant-based fibers
Domestic Extraction Used - Primary Crops – Cottonseed	kt	30	Cotton	Oil seeds
Domestic Extraction Used - Primary Crops - Cow peas, dry	kt	16	cowpea	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Cranberries	kt	40	temperate fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Cucumbers and Gherkins	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Currants	kt	40	temperate fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Dates	kt	39	tropical fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Eggplants	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Fibre Crops nes	kt	31	other fibre crops	Plant-based fibers
Domestic Extraction Used - Primary Crops – Figs	kt	39	tropical fruit	Vegetables, fruit, nuts

Domestic Extraction Used - Primary Crops - Flax Fibre and Tow	kt	31	other fibre crops	Plant-based fibers
Domestic Extraction Used - Primary Crops – Fonio	kt	8	other cereals	Cereal grains nec
Domestic Extraction Used - Primary Crops - Fruit Fresh Nes	kt	40	temperate fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Fruit, tropical fresh nes	kt	39	tropical fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Garlic	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Ginger	kt	42	rest of crops	Crops nec
Domestic Extraction Used - Primary Crops – Gooseberries	kt	40	temperate fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Grapefruit and Pomelos	kt	39	tropical fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Grapes	kt	40	temperate fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Groundnuts in Shell	kt	21	groundnut	Oil seeds
Domestic Extraction Used - Primary Crops – Hazelnuts	kt	42	rest of crops	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Hemp Fibre and Tow	kt	31	other fibre crops	Plant-based fibers
Domestic Extraction Used - Primary Crops – Hempseed	kt	27	other oil crops	Oil seeds
Domestic Extraction Used - Primary Crops – Hops	kt	42	rest of crops	Crops nec
Domestic Extraction Used - Primary Crops - Jojoba Seeds	kt	27	other oil crops	Oil seeds
Domestic Extraction Used - Primary Crops - Jute and Jute-like Fibres	kt	31	other fibre crops	Plant-based fibers
Domestic Extraction Used - Primary Crops - Kapok Fibre	kt	31	other fibre crops	Plant-based fibers
Domestic Extraction Used - Primary Crops - Karite Nuts	kt	27	other oil crops	Oil seeds
Domestic Extraction Used - Primary Crops - Kiwi Fruit	kt	40	temperate fruit	Vegetables, fruit, nuts

Domestic Extraction Used - Primary Crops – Kolanuts	kt	42	rest of crops	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Leeks and other Alliac. Veg.	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Leguminous vegetables, nes	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Lemons and Limes	kt	39	tropical fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Lentils	kt	18	Lentil	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Lettuce	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Linseed	kt	27	other oil crops	Oil seeds
Domestic Extraction Used - Primary Crops – Lupins	kt	19	other pulses	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Maize	kt	3	Maize	Cereal grains nec
Domestic Extraction Used - Primary Crops - Maize, green	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Mangoes, mangosteens, guavas	kt	39	tropical fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Mate	kt	42	rest of crops	Crops nec
Domestic Extraction Used - Primary Crops – Melonseed	kt	27	other oil crops	Oil seeds
Domestic Extraction Used - Primary Crops – Millet	kt	5	pearl millet	Cereal grains nec
Domestic Extraction Used - Primary Crops - Mixed Grain	kt	8	other cereals	Cereal grains nec
Domestic Extraction Used - Primary Crops – Mushrooms	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Mustard Seed	kt	25	rapeseed	Oil seeds
Domestic Extraction Used - Primary Crops - Natural Rubber	kt	42	rest of crops	Crops nec
Domestic Extraction Used - Primary Crops - Nutmeg, mace and cardamoms	kt	42	rest of crops	Crops nec
Domestic Extraction Used - Primary Crops - Nuts, nes	kt	42	rest of crops	Vegetables, fruit, nuts

Domestic Extraction Used - Primary Crops – Oats	kt	8	other cereals	Cereal grains nec
Domestic Extraction Used - Primary Crops - Oil Palm Fruit	kt	23	oilpalm	Oil seeds
Domestic Extraction Used - Primary Crops - Oilseeds nec	kt	27	other oil crops	Oil seeds
Domestic Extraction Used - Primary Crops – Okra	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Olives	kt	27	other oil crops	Oil seeds
Domestic Extraction Used - Primary Crops – Onions	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Onions, dry	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Oranges	kt	39	tropical fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Other Bastfibres	kt	31	other fibre crops	Plant-based fibers
Domestic Extraction Used - Primary Crops - Other melons	kt	39	tropical fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Papayas	kt	39	tropical fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Peaches and Nectarines	kt	40	temperate fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Pears	kt	40	temperate fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Peas, dry	kt	19	other pulses	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Peas, Green	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Pepper	kt	42	rest of crops	Crops nec
Domestic Extraction Used - Primary Crops – Peppermint	kt	42	rest of crops	Crops nec
Domestic Extraction Used - Primary Crops – Persimmons	kt	39	tropical fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Pigeon peas	kt	17	pigeonpea	Vegetables, fruit, nuts

Domestic Extraction Used - Primary Crops – Pineapples	kt	39	tropical fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Pistachios	kt	42	rest of crops	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Plantains	kt	38	plantain	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Plums	kt	40	temperate fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Pome fruit, nes	kt	40	temperate fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Poppy Seed	kt	27	other oil crops	Oil seeds
Domestic Extraction Used - Primary Crops – Potatoes	kt	9	Potato	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Pulses nec	kt	19	other pulses	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Pumpkins, Squash, Gourds	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Pyrethrum, Dried Flowers	kt	42	rest of crops	Crops nec
Domestic Extraction Used - Primary Crops – Quinces	kt	40	temperate fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Quinoa	kt	8	other cereals	Cereal grains nec
Domestic Extraction Used - Primary Crops – Ramie	kt	31	other fibre crops	Plant-based fibers
Domestic Extraction Used - Primary Crops – Rapeseed	kt	25	rapeseed	Oil seeds
Domestic Extraction Used - Primary Crops – Raspberries	kt	40	temperate fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Rice	kt	2	Rice	Paddy rice
Domestic Extraction Used - Primary Crops - Roots and Tubers, nes	kt	13	other roots	Cereal grains nec
Domestic Extraction Used - Primary Crops – Rye	kt	8	other cereals	Cereal grains nec
Domestic Extraction Used - Primary Crops - Safflower Seed	kt	27	other oil crops	Oil seeds

Domestic Extraction Used - Primary Crops - Sesame Seed	kt	26	sesameseed	Oil seeds
Domestic Extraction Used - Primary Crops – Sisal	kt	31	other fibre crops	Plant-based fibers
Domestic Extraction Used - Primary Crops – Sorghum	kt	7	sorghum	Cereal grains nec
Domestic Extraction Used - Primary Crops - Sour Cherries	kt	40	temperate fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Soybeans	kt	20	soybean	Oil seeds
Domestic Extraction Used - Primary Crops - Spices nec	kt	42	rest of crops	Crops nec
Domestic Extraction Used - Primary Crops – Spinach	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Stone Fruit nec,	kt	40	temperate fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Strawberries	kt	40	temperate fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - String beans	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Sugar Beets	kt	29	sugarbeet	Sugar cane, sugar beet
Domestic Extraction Used - Primary Crops - Sugar Cane	kt	28	sugarcane	Sugar cane, sugar beet
Domestic Extraction Used - Primary Crops - Sugar Crops nes	kt	42	rest of crops	Sugar cane, sugar beet
Domestic Extraction Used - Primary Crops - Sunflower Seed	kt	24	sunflower	Oil seeds
Domestic Extraction Used - Primary Crops - Sweet Potatoes	kt	10	sweet potato	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops - Tallowtree Seeds	kt	27	other oil crops	Oil seeds
Domestic Extraction Used - Primary Crops - Tang. Mand Clement. Satsma	kt	39	tropical fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Taro	kt	13	other roots	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Tea	kt	35	Tea	Crops nec
Domestic Extraction Used - Primary Crops - Tea nes	kt	35	Tea	Crops nec

Domestic Extraction Used - Primary Crops - Tobacco Leaves	kt	36	tobacco	Crops nec
Domestic Extraction Used - Primary Crops – Tomatoes	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Triticale	kt	8	other cereals	Cereal grains nec
Domestic Extraction Used - Primary Crops - Tung Nuts	kt	27	other oil crops	Oil seeds
Domestic Extraction Used - Primary Crops – Vanilla	kt	42	rest of crops	Crops nec
Domestic Extraction Used - Primary Crops - Vegetables Fresh nec	kt	41	vegetables	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Vetches	kt	19	other pulses	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Walnuts	kt	42	rest of crops	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Watermelons	kt	39	tropical fruit	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Wheat	kt	1	Wheat	Wheat
Domestic Extraction Used - Primary Crops – Yams	kt	11	Yams	Vegetables, fruit, nuts
Domestic Extraction Used - Primary Crops – Yautia	kt	13	other roots	Vegetables, fruit, nuts

Table S 8.11. Mapping relationship between EXIOABSE account with FAOSTAT product of livestock

EXIOBASE sector number	EXIOBASE name	FAOSTAT product names
11	Poultry	Eggs, hen, in shell
14	Raw milk	Milk, whole fresh cow; Milk, whole fresh goat; Milk, whole fresh sheep
43	Products of meat cattle	Hides, cattle, fresh; Meat indigenous, cattle
44	Products of meat pigs	Meat indigenous, pig.
45	Products of meat poultry	Meat indigenous, chicken; Meat indigenous, duck
46	Meat products nec	Meat indigenous, goat; Skins, goat, fresh; Meat indigenous, sheep; Skins, sheep, fresh.

Table S 8.12. Mapping relationship between countries in FAOSTAT with regions in EXIOABSE for livestock

FAOSTAT countries	EXIOBASE regions	Region abbreviation in EXIOBASE
Austria	Austria	AT
Belgium	Belgium	BE
Bulgaria	Bulgaria	BG
Cyprus	Cyprus	CY
Czechia	Czech Republic	CZ
Germany	Germany	DE
Denmark	Denmark	DK
Estonia	Estonia	EE
Spain	Spain	ES
Finland	Finland	FI
France	France	FR
Greece	Greece	GR
Croatia	Croatia	HR
Hungary	Hungary	HU
Ireland	Ireland	IE
Italy	Italy	IT
Lithuania	Lithuania	LT
Luxembourg	Luxembourg	LU
Latvia	Latvia	LV
Malta	Malta	MT
Netherlands	Netherlands	NL
Netherlands Antilles (former)	Netherlands	NL
Poland	Poland	PL
Portugal	Portugal	PT

Romania	Romania	RO
Sweden	Sweden	SE
Slovenia	Slovenia	SI
Slovakia	Slovakia	SK
United Kingdom	United Kingdom	GB
United States of America	United States	US
Japan	Japan	JP
China, Hong Kong SAR	China	CN
China, mainland	China	CN
Canada	Canada	CA
Republic of Korea	South Korea	KR
Brazil	Brazil	BR
India	India	IN
Mexico	Mexico	MX
Russian Federation	Russia	RU
Australia	Australia	AU
Switzerland	Switzerland	CH
Turkey	Turkey	TR
China, Taiwan Province of	Taiwan	TW
Norway	Norway	NO
Indonesia	Indonesia	ID
South Africa	South Africa	ZA
New Caledonia	RoW Asia and Pacific	WA
Afghanistan	RoW Asia and Pacific	WA
American Samoa	RoW Asia and Pacific	WA
Armenia	RoW Asia and Pacific	WA

Azerbaijan	RoW Asia and Pacific	WA
Bangladesh	RoW Asia and Pacific	WA
Bhutan	RoW Asia and Pacific	WA
Brunei	RoW Asia and Pacific	WA
Cambodia	RoW Asia and Pacific	WA
Cook Islands	RoW Asia and Pacific	WA
Democratic People's Republic of Korea	RoW Asia and Pacific	WA
Fiji	RoW Asia and Pacific	WA
French Polynesia	RoW Asia and Pacific	WA
Georgia	RoW Asia and Pacific	WA
Guam	RoW Asia and Pacific	WA
Kazakhstan	RoW Asia and Pacific	WA
Kyrgyzstan	RoW Asia and Pacific	WA
Lao People's Democratic Republic	RoW Asia and Pacific	WA
Malaysia	RoW Asia and Pacific	WA
Micronesia (Federated States of)	RoW Asia and Pacific	WA
Mongolia	RoW Asia and Pacific	WA
Myanmar	RoW Asia and Pacific	WA
Nepal	RoW Asia and Pacific	WA
New Zealand	RoW Asia and Pacific	WA
Niue	RoW Asia and Pacific	WA
Norfolk Island	RoW Asia and Pacific	WA
Pakistan	RoW Asia and Pacific	WA
Papua New Guinea	RoW Asia and Pacific	WA
Philippines	RoW Asia and Pacific	WA
Samoa	RoW Asia and Pacific	WA

Singapore	RoW Asia and Pacific	WA
Solomon Islands	RoW Asia and Pacific	WA
Sri Lanka	RoW Asia and Pacific	WA
Tajikistan	RoW Asia and Pacific	WA
Thailand	RoW Asia and Pacific	WA
Timor-Leste	RoW Asia and Pacific	WA
Tonga	RoW Asia and Pacific	WA
Turkmenistan	RoW Asia and Pacific	WA
Uzbekistan	RoW Asia and Pacific	WA
Vanuatu	RoW Asia and Pacific	WA
Viet Nam	RoW Asia and Pacific	WA
Wallis and Futuna Islands	RoW Asia and Pacific	WA
Antigua and Barbuda	RoW America	WL
Argentina	RoW America	WL
Bahamas	RoW America	WL
Barbados	RoW America	WL
Belize	RoW America	WL
Bermuda	RoW America	WL
Bolivia	RoW America	WL
British Virgin Islands	RoW America	WL
Cayman Islands	RoW America	WL
Chile	RoW America	WL
Colombia	RoW America	WL
Costa Rica	RoW America	WL
Cuba	RoW America	WL
Dominica	RoW America	WL

Dominican Republic	RoW America	WL
Ecuador	RoW America	WL
El Salvador	RoW America	WL
Falkland Islands (Malvinas)	RoW America	WL
French Guiana	RoW America	WL
Greenland	RoW America	WL
Grenada	RoW America	WL
Guadeloupe	RoW America	WL
Guatemala	RoW America	WL
Guyana	RoW America	WL
Haiti	RoW America	WL
Honduras	RoW America	WL
Jamaica	RoW America	WL
Martinique	RoW America	WL
Montserrat	RoW America	WL
Nicaragua	RoW America	WL
Panama	RoW America	WL
Paraguay	RoW America	WL
Peru	RoW America	WL
Puerto Rico	RoW America	WL
Saint Kitts and Nevis	RoW America	WL
Saint Lucia	RoW America	WL
Saint Pierre and Miquelon	RoW America	WL
Saint Vincent and the Grenadines	RoW America	WL
Suriname	RoW America	WL
Trinidad and Tobago	RoW America	WL

United States Virgin Islands	RoW America	WL
Uruguay	RoW America	WL
Venezuela (Bolivarian Republic of)	RoW America	WL
Albania	RoW Europe	WE
Belarus	RoW Europe	WE
Bosnia and Herzegovina	RoW Europe	WE
Faroe Islands	RoW Europe	WE
Iceland	RoW Europe	WE
Liechtenstein	RoW Europe	WE
Montenegro	RoW Europe	WE
Republic of Moldova	RoW Europe	WE
Serbia	RoW Europe	WE
The former Yugoslav Republic of Macedonia	RoW Europe	WE
Ukraine	RoW Europe	WE
Algeria	RoW Africa	WF
Angola	RoW Africa	WF
Benin	RoW Africa	WF
Botswana	RoW Africa	WF
Burkina Faso	RoW Africa	WF
Burundi	RoW Africa	WF
C+¦te d'Ivoire	RoW Africa	WF
Cabo Verde	RoW Africa	WF
Cameroon	RoW Africa	WF
Central African Republic	RoW Africa	WF
Chad	RoW Africa	WF
Comoros	RoW Africa	WF

Congo	RoW Africa	WF
Democratic Republic of the Congo	RoW Africa	WF
Djibouti	RoW Africa	WF
Equatorial Guinea	RoW Africa	WF
Eritrea	RoW Africa	WF
Ethiopia	RoW Africa	WF
Gabon	RoW Africa	WF
Gambia	RoW Africa	WF
Ghana	RoW Africa	WF
Guinea	RoW Africa	WF
Guinea-Bissau	RoW Africa	WF
Kenya	RoW Africa	WF
Lesotho	RoW Africa	WF
Liberia	RoW Africa	WF
Libya	RoW Africa	WF
Madagascar	RoW Africa	WF
Malawi	RoW Africa	WF
Mali	RoW Africa	WF
Mauritania	RoW Africa	WF
Mauritius	RoW Africa	WF
Morocco	RoW Africa	WF
Mozambique	RoW Africa	WF
Namibia	RoW Africa	WF
Niger	RoW Africa	WF
Nigeria	RoW Africa	WF
Reunion	RoW Africa	WF

Rwanda	RoW Africa	WF
Saint Helena, Ascension and Tristan da Cunha	RoW Africa	WF
Sao Tome and Principe	RoW Africa	WF
Senegal	RoW Africa	WF
Seychelles	RoW Africa	WF
Sierra Leone	RoW Africa	WF
Somalia	RoW Africa	WF
Sudan (former)	RoW Africa	WF
Swaziland	RoW Africa	WF
Togo	RoW Africa	WF
Tunisia	RoW Africa	WF
Uganda	RoW Africa	WF
United Republic of Tanzania	RoW Africa	WF
Western Sahara	RoW Africa	WF
Zambia	RoW Africa	WF
Zimbabwe	RoW Africa	WF
Bahrain	RoW Middle East	WM
Egypt	RoW Middle East	WM
Iran (Islamic Republic of)	RoW Middle East	WM
Iraq	RoW Middle East	WM
Israel	RoW Middle East	WM
Jordan	RoW Middle East	WM
Kuwait	RoW Middle East	WM
Lebanon	RoW Middle East	WM
Occupied Palestinian Territory	RoW Middle East	WM
Oman	RoW Middle East	WM

Qatar	RoW Middle East	WM
Saudi Arabia	RoW Middle East	WM
Syrian Arab Republic	RoW Middle East	WM
United Arab Emirates	RoW Middle East	WM
Yemen	RoW Middle East	WM

8.3 Supporting information to chapter 4

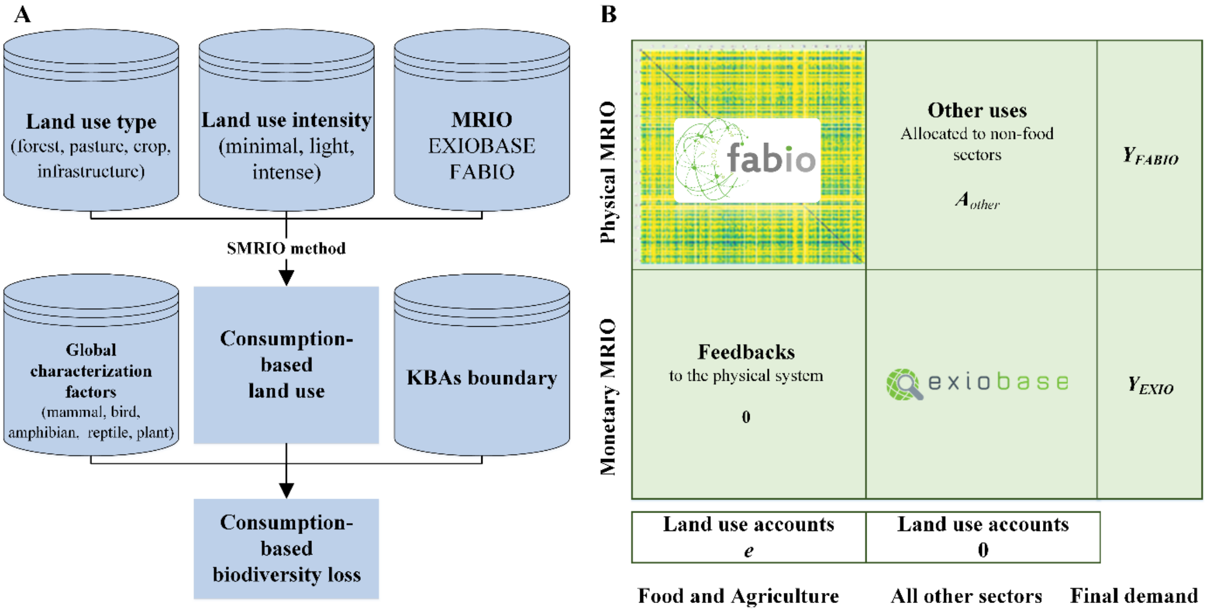

Figure S 8.12. Schematic of the methodology in general (a), and of linking FABIO and EXIOBASE (b).

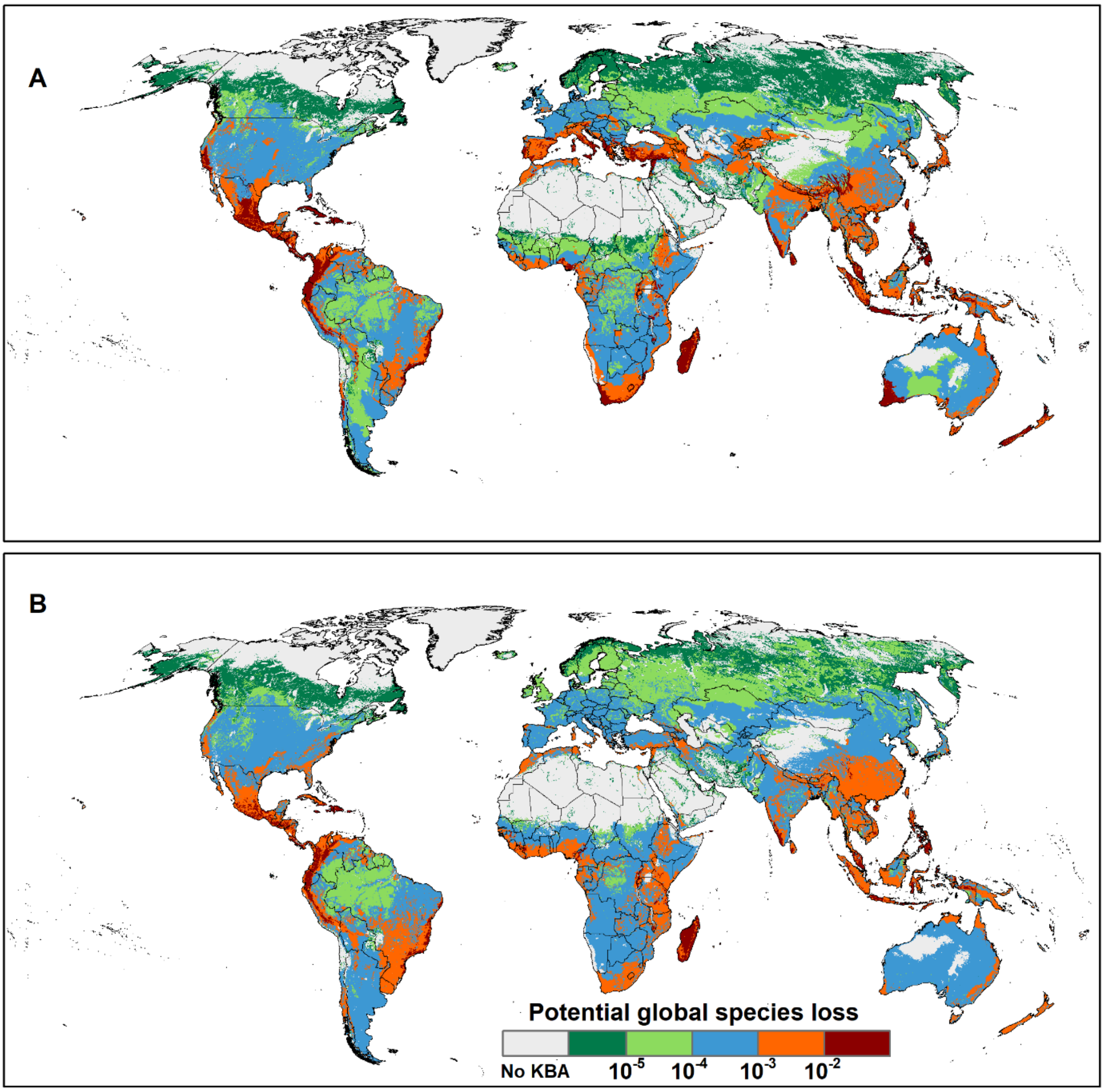

Figure S 8.13. Spatial distribution of potential global species loss driven by land use inside and outside KBAs for a) plants, and b) vertebrates (mammals + birds + amphibians + reptiles). The spatial resolution is 5 arc min.

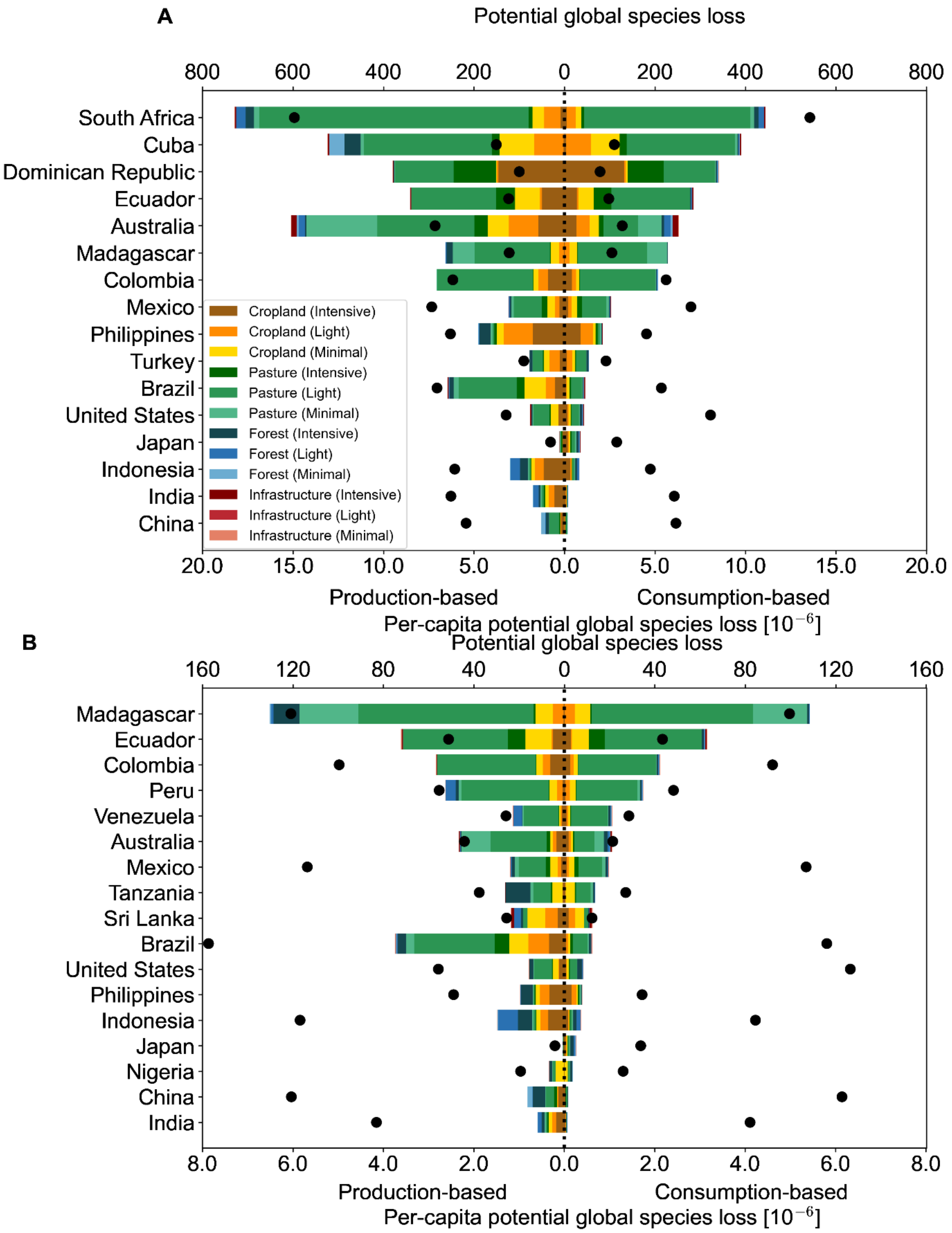

Figure S 8.14. The potential global species loss from land use inside and outside KBAs for plants (a) and vertebrates (b) (mammals, birds, amphibians, and reptiles). On each *x*-axis (bottom and top of figures), the production-based perspective is shown to the left of zero and the consumption-based perspective to the right. The *y*-axis lists the top 15 countries/regions with the largest consumption-based or production-based biodiversity loss from land use within and outside KBAs at the national level. The bar shows the per-capita value of biodiversity loss per land type and land use intensity. The circles show the total national biodiversity loss with a value shown by the upper *x*-axes on the top of each plot.

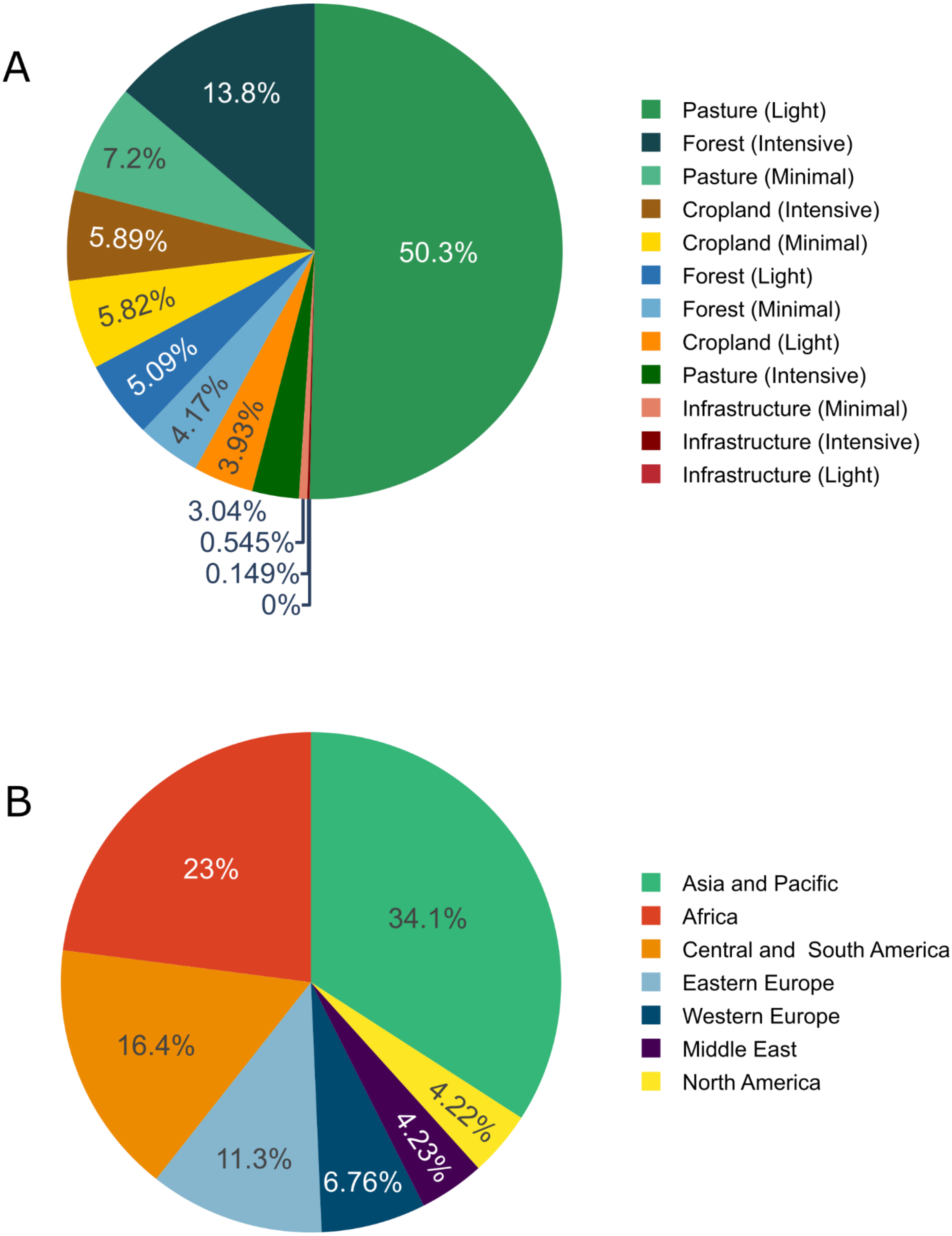

Figure S 8.15. Land use within KBAs with different land use types and land use intensities (a) and in different regions (b).

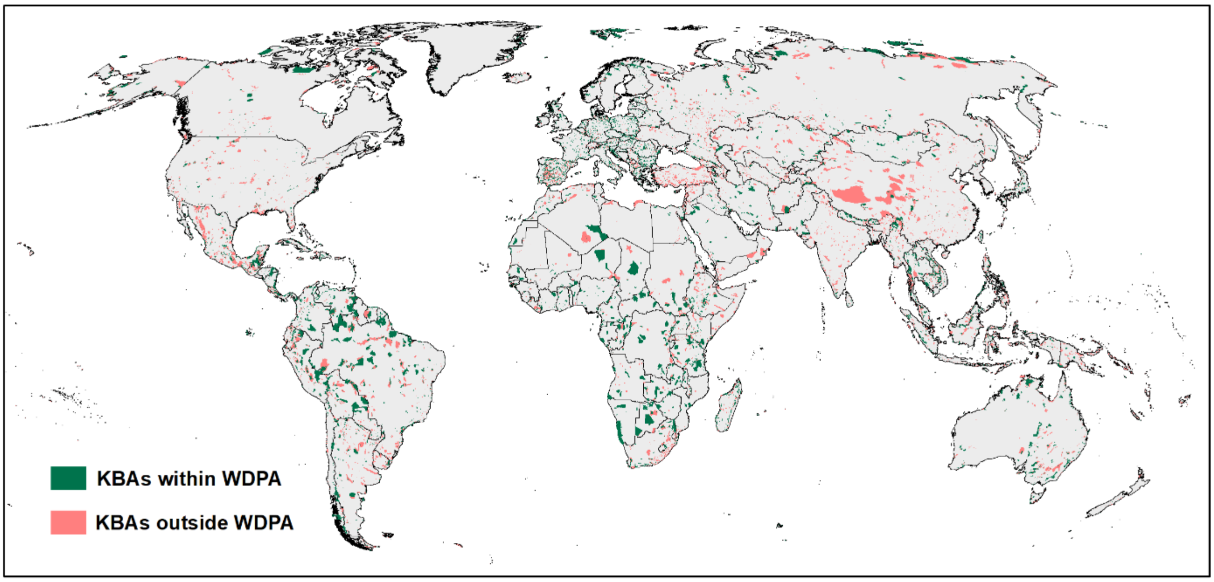

Figure S 8.16. Intersections between KBAs and the World Database on Protected Areas (WDPA).

8.4 Supporting information to chapter 5

8.4.1 Supplementary Methods

Biomass carbon and soil organic carbon in current vegetation

The calculation of aboveground biomass carbon (AGBC) and belowground biomass carbon (BGBC) is based on the latest harmonized carbon density map in the year 2010 developed by Spawn et al[358]. For herbaceous crops, Spawn et al. employed gridded crop maps from EarthStat [35], and we used the latest crop maps from Spatial Production Allocation Model (SPAM) [390] in 2010 and method from Spawn et al. [358]to get the latest AGBC and BGBC maps of herbaceous crops. For woody crops and pasture, we extract AGBC and BGBC from the latest harmonized carbon density maps directly.

Primary crops and fodder:

The production and harvested area of 163 types of primary crops and 16 types of fodder crops in 2010 come from FAOSTAT [357]. The fodder crops are not available in FAOSTAT now, and are provided by one of developers of The Food and Agriculture Biomass Input-Output model (FABIO) [36]. We then use the SPAM [390] to build a spatially-explicit picture of crop production. SPAM employs a cross-entropy approach to make estimates of 42 crop maps in 2010 at 5 arc min resolution. Since "Pearl Millet" and "Small Millet" are not split in FAOSTAT, we aggregate them into millet; similarly "Arabica Coffee" and "Robusta Coffee" are not split and we aggregate them into "Coffee". These 40 crops are aggregated from an average of 163 types of primary crops contained in the FAOSTAT database between 2009 and 2011. Therefore, we used national data from FAOSTAT in 2010 to calibrate the SPAM for each country. However, since SPAM does not include fodder crop maps, we use EarthStat fodder maps [35] at 5 arc min resolution in 2000. We aggregate the 16 fodder maps into one fodder map for ease of analysis.

Pasture

There are many ways to estimate pasture for grazing. Ramankutty et al. created a map in which they estimate the percentage of pasture per grid cell at 5 min resolution [35] in 2000. Sloat et al., updated this map to the year 2010 at 500 meters resolution [393]. They considered a grid cell to be pasture if it fell into a livestock category on the global livestock production systems (GLPS) map and also contained at least 30% pasture by area [393]. Marques et al.,[12] used pasture map from Ramankutty et al.,[35] as permanent pasture, and excluded non-productive area (below NPP over 20 g C m^{-2} yr^{-1}) is used to feed livestock in the year 2000. In the end, we employed the pasture map developed by Sloat et al. [393] because their dataset is the latest and the time is in line with our research. We assume pasture layer was capped if all land-use types (cropland, infrastructure, and forest) fill 100% of the grid cell. For forest, we employed fractional tree cover from MODIS in 2010 [426]. We linearly stretched values such that 80% was treated as complete tree cover (100%), since MODIS tree cover estimates saturate at around 80%, following Spawn et al.[358]. For infrastructure, we used ESA CCI Land cover Maps at 300 meters resolution in 2010 [427].

GHG emissions

For animal-specific sectors, this includes: "Enteric Fermentation", "Manure Management", "Manure applied to Soils", and "Manure left on Pasture". For crop-specific sectors, this includes: "Rice Cultivation", "Crop Residues", and "Burning - Crop Residues". There are two outstanding, high-emission sectors: "Synthetic Fertilizers", and "Energy Use" which are not allocated to specific agricultural sectors. In FAOSTAT, GHG emission of "Synthetic Fertilizers" is only derived from nitrogen fertilizers, so we first classify their GHG emissions into 28 countries/regions, and 13 crop groups based on the amount of nitrogen fertilizer use from the International Fertilizer Association (IFA) in 2010 [428]. Mapping relationship of countries and crops between FABIO and IFA see Tables S5 and S6. We then allocate GHG emission of “Synthetic Fertilizers” of 28 countries/regions, and 13 crop groups into separated countries and agricultural sectors in FABIO based on the monetary value of crops in each group from FAOSTAT [357]. Similarly, we allocate CO_2, CH_4, and N_2O from the “Energy Use” sector into 49 countries/regions and 14 agricultural sectors based on the combustion emissions of CO_2, CH_4, N_2O in EXIOBASE v3.6. Mapping relationship of countries and sectors between FABIO and EXIOBASE see Supplementary Tables S7 and S8. We then allocate these cases from “Energy Use” into agricultural sectors and countries using FABIO and based on the monetary value of crops from FAOSTAT in every group.

8.4.2 **Supplementary Discussion**

Potential opportunities for carbon sequestration.

Climate-smart agriculture may provide another opportunity to increase carbon benefits [429]. For example, novel plants like intermediate wheatgrass (*Thinopyrum intermedium* (Host) Barkworth & D.R.Dewey) is an emerging cool-season perennial grain (the name for commercialized grain is “Kernza”) and forage dual-use grass, and its extensive root system can improve belowground carbon fixing and reduce soil erosion [430]. Intermediate wheatgrass is becoming commercially available to farmers for some areas in the US [431]. A further opportunity is biochar. While carbon stocks will saturate when the land restores to mature and stable vegetation, biochar can break the biophysical limits of carbon sequestration[379]. Feedstocks for biochar come from residues of forest/crop/pasture, animal manure, and food waste[379]. Removing forest residue can reduce risks of wildfire, but may disturb habitats of some fungi and wildlife, along with other ecosystem services [379]. This represents a tradeoff among carbon sequestration and other ecosystem services [379]. New technologies in agricultural production can also help to mitigate climate change. For example, 3-nitrooxypropanol (3NOP), a methane inhibitor, can persistently decrease enteric methane emissions by 30% under industry-relevant conditions without affecting animal productivity negatively [432], and has been approved as a feed additive in the European Union [433].

Potential carbon offset.

Here, we focus on dietary change in high-income countries where most food supply is higher than the recommendation in the EAT diet, and the dietary change could increase carbon sequestration and reduce CO2 emission. However, the carbon benefit may be offset by population growth and malnutrition in some low- and middle-income countries in the long term [327]. For example, most low- and middle-income countries face a severe double burden of malnutrition which means simultaneous manifestation of both undernutrition and overweight and obesity [434]. The obesity in low- and middle-income countries is due to overconsumption of cheap ultra-processed food and beverages which is an unhealthy diet [434]. The EAT diet is not suitable in low-income countries because they cannot afford it, and it estimated at least 1.58 billion people are not able to pay for the cost of the EAT diet in the world [397]. People will consume more food with income growth, especially animal products in low- and middle-income countries [45]. In addition population growth low- and middle-income countries will increase food needs further. For example, population is projected to increase by 199% (1026·04 million in 2017 to 3071·21 million in 2100) in Sub-Saharan Africa [420]. The increasing food demand in low- and middle-income countries will offset carbon benefit from dietary change in high-income countries.

Another carbon offset is food waste in high-income countries. EAT diet recommends per-capita food intake instead of food purchase. Pre-capita food waste is positively related to per-capita income, and most food waste occurs in consumption stage in high-income countries because of overstocking, and too much cooking or serving [435]. In addition, healthier diets would cause more food waste because healthier diets need more consumption of perishable produce such as fruit and vegetables, which has substantial hidden costs from food waste [436]. Therefore, it is very necessary to halt food waste and loss. It is estimated about one third of global food is lost or wasted [222]. If reducing 50% of global food waste and loss, another 0.9 Pg CO_2e yr^{-1} would be mitigated [437].

Recently, organic food consumption and organic agriculture production are surging in high-income countries because they are more environmentally friendly (e.g. less fertilizer or pesticide input, and fewer biodiversity losses) also higher price compared to conventional farming [438,439]. However, organic production has lower yield which means it needs more land use to satisfy the same food demand [438,439]. The high quality and environmentally friendly food consumption is at the expense of carbon benefit.

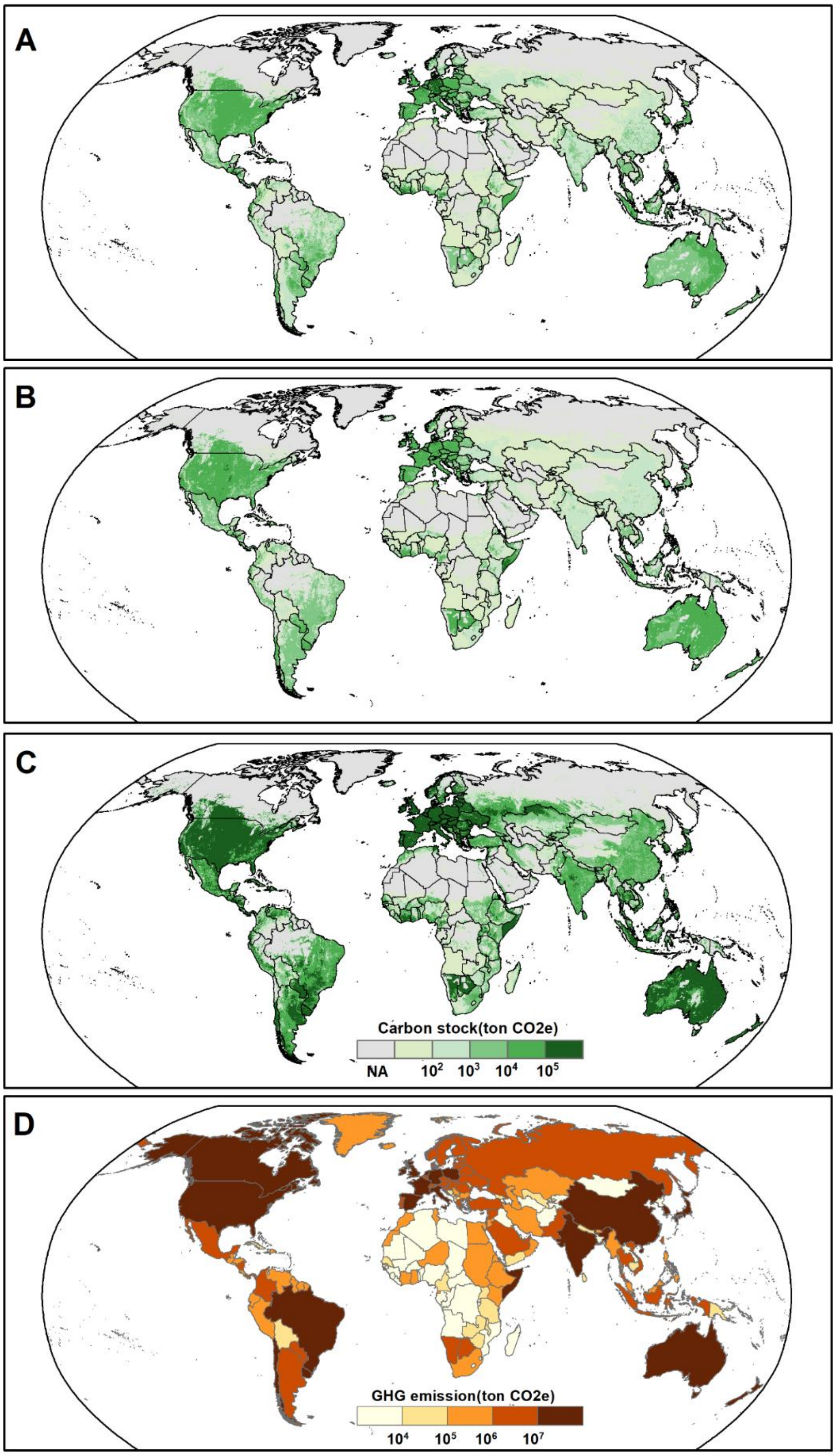

Figure S 8.17. Aboveground biomass carbon (AGBC, A), belowground biomass carbon (BGBC, B), soil organic carbon (SOC, C) and GHG emission (D) embodied in current national average diets of high-income countries.

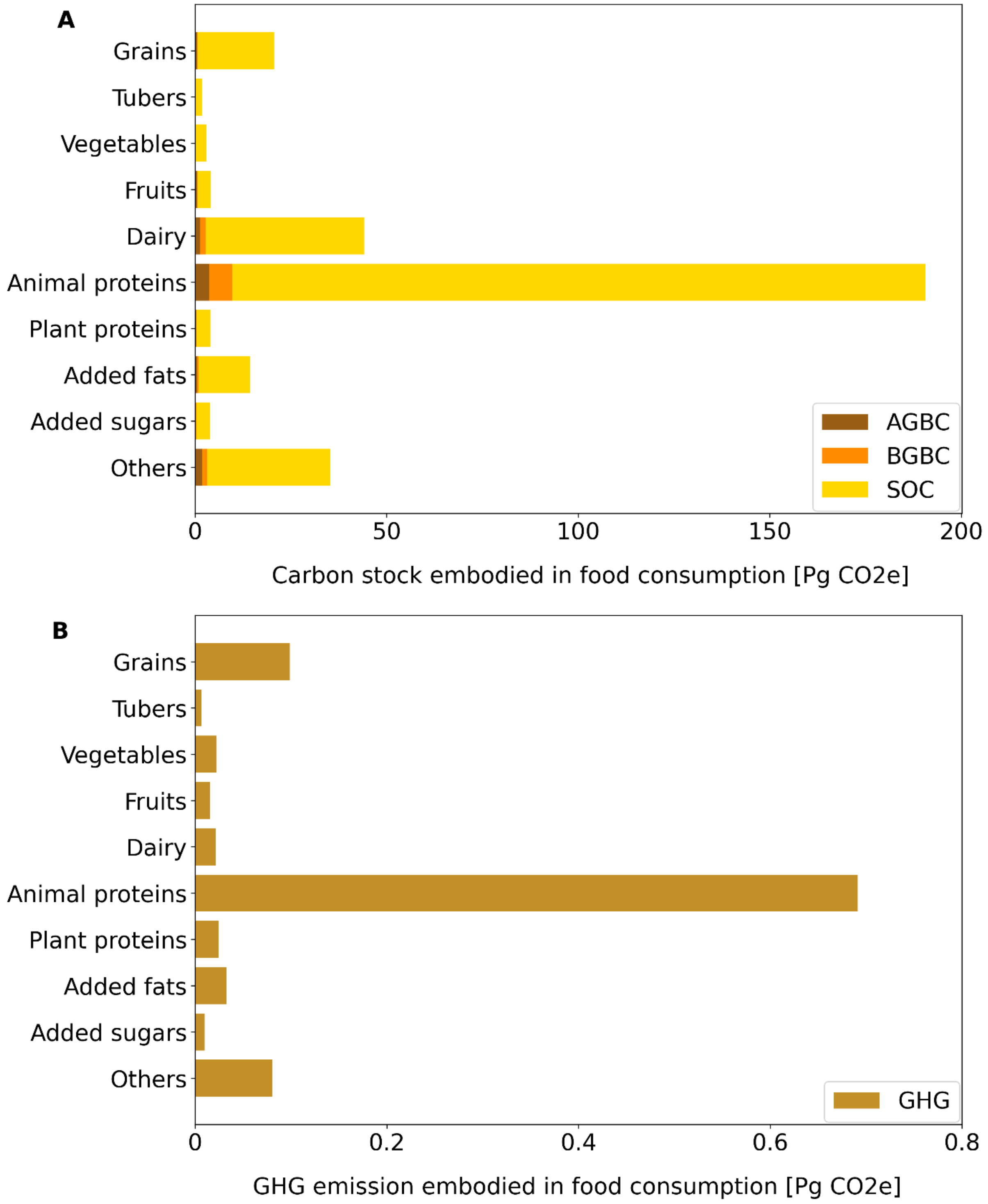

Figure S 8.18. Embodied carbon stocks (A) and GHG emission flows (B) in national average diets for high-income countries by food category. Carbon stock means aboveground biomass carbon (AGBC), belowground biomass carbon (BGBC), and soil organic carbon (SOC) in present agricultural production related vegetation (primary crops, fodder, and pasture) used for human food consumption.

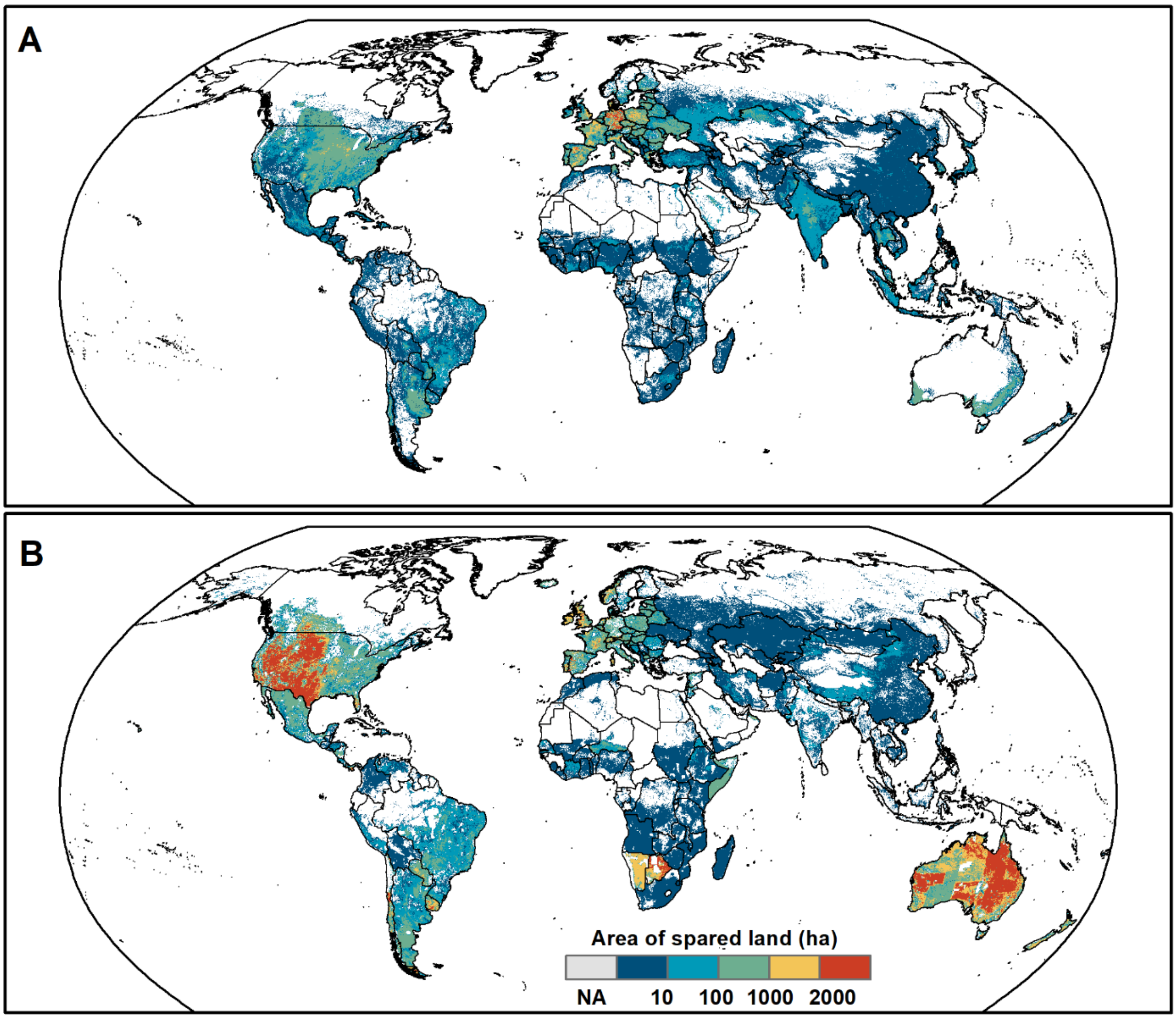

Figure S 8.19. Area of spared land due to dietary shift from national average diets to EAT diet in high-income countries for cropland (A) and pastureland (B).

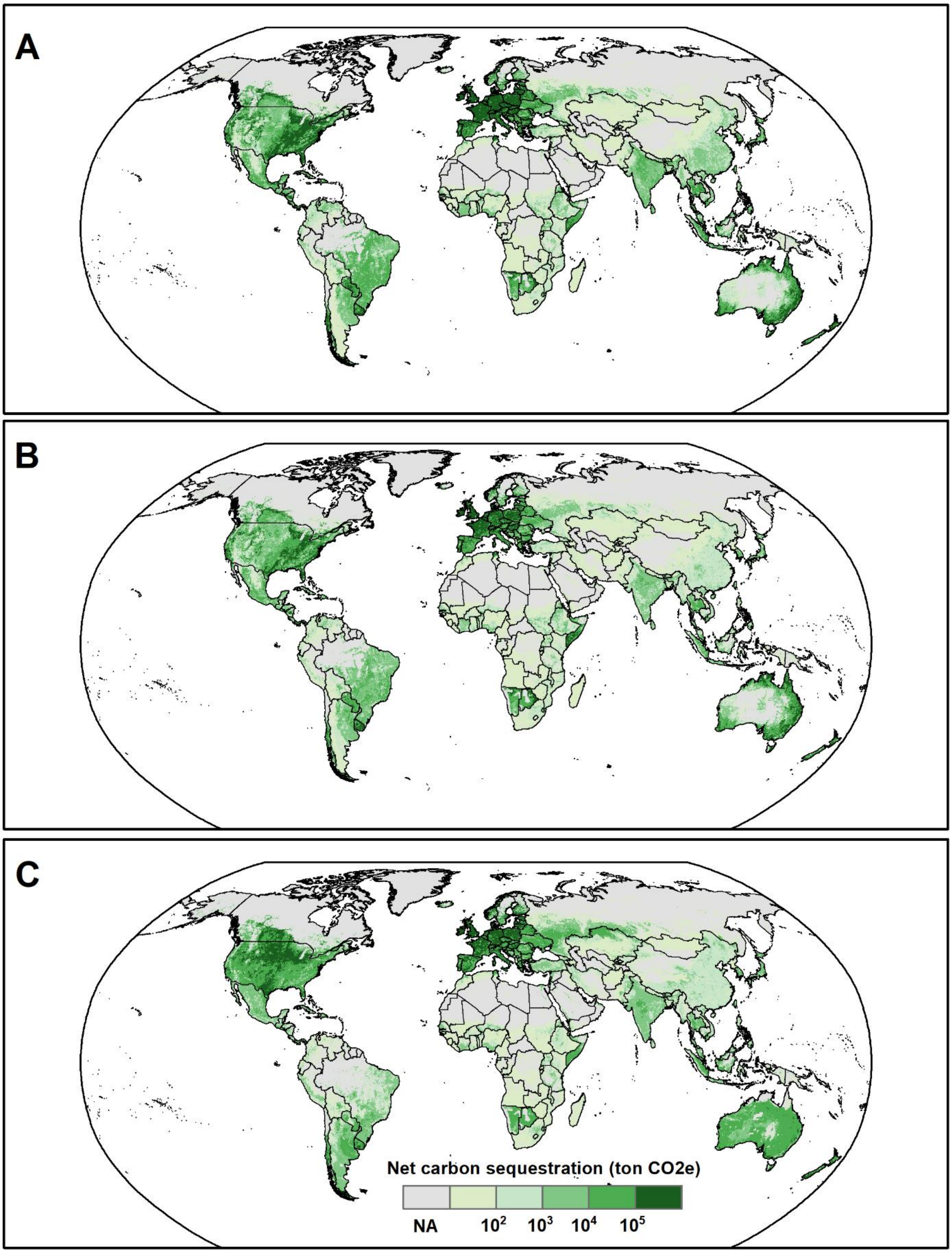

Figure S 8.20. Net carbon sequestration due to dietary shift from national average diets to EAT diet in high-income countries. Increasing amount of carbon sequestration in spared land due to dietary change for AGBC (A), BGBC (B), SOC (C).

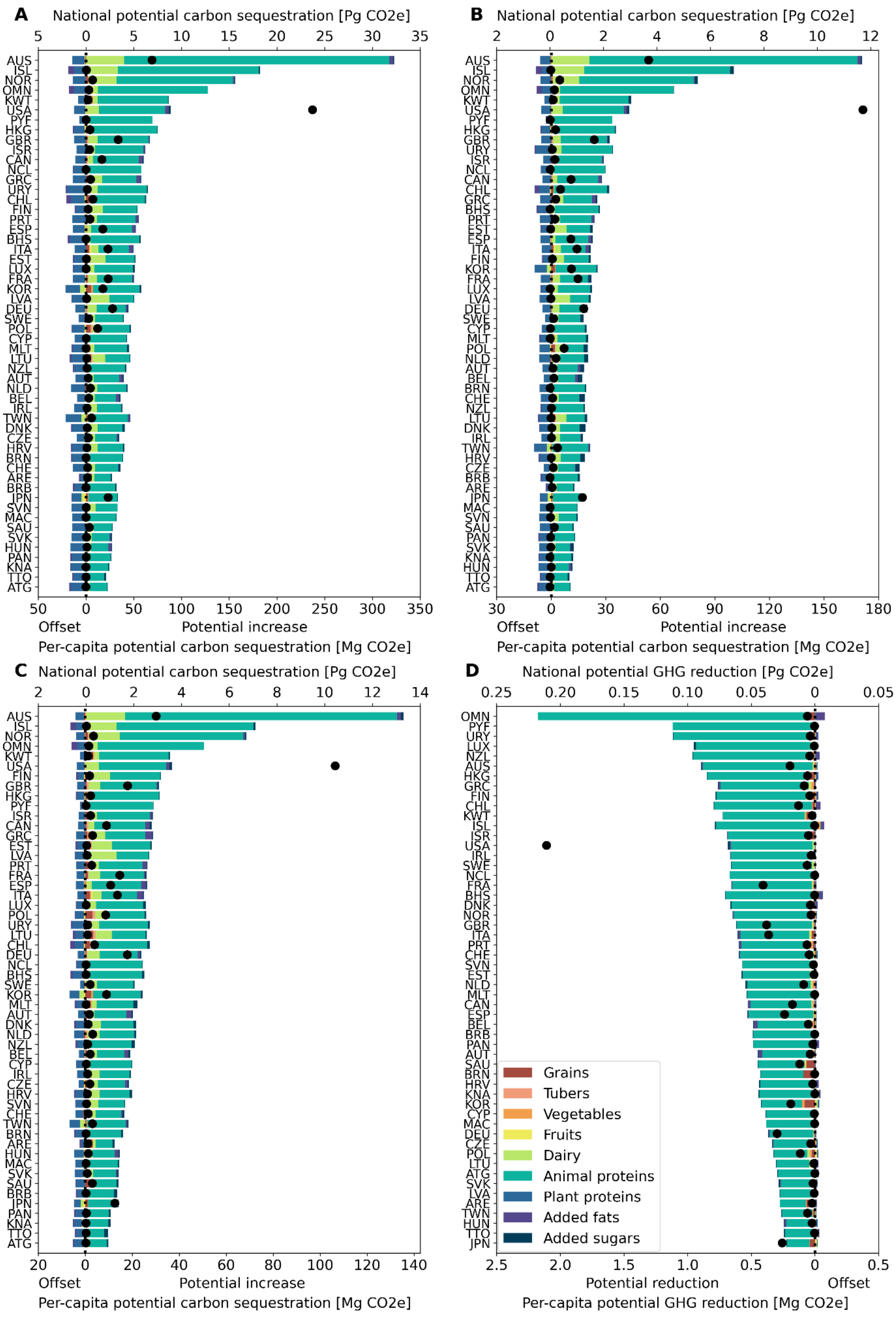

Figure S 8.21. National and Per-capita net carbon benefit due to dietary shift from national average diets to EAT diet in individual high-income country by food category. Increasing amount of carbon sequestration due to dietary change for AGBC (A), BGBC (B), SOC (C), and reducing amount of GHG emission (D) by food category. The bar means per-capita carbon sequestration and GHG emission change by food categories, and the dot means national net carbon sequestration and GHG emission change. The potential increase of carbon sequestration means carbon sequestration in potential natural vegetation minus that of current agricultural vegetation. The offset of carbon sequestration means carbon sequestration in potential natural vegetation minus that of increased agricultural vegetation. The carbon reduction of GHG emission means the GHG reduction due to reduction of food categories, and the offset means the GHG increase due to increase of food categories.