Ambio

Electronic Supplementary Material
This supplementary material has not been peer reviewed

Title: **Exploring sustainable scenarios in debt-based social–ecological systems: The case for palm oil production in Indonesia**.

Julen Gonzalez-Redin, J. Gareth Polhill, Terence P. Dawson, Rosemary Hill, Iain J. Gordon

Supporting Information

Table S1: Abbreviations and terms use throughout the main paper and SI document.

Abbreviation	Full term	Abbreviation	Full term
GHG	Green House Gas	SF	Sustainable Futures
CPO	Crude Palm Oil	ABLUM	Agent-Based Land-Use Model
ABM	Agent-Based Model	TRACE	
SES	Social-Ecological System	ODD	Overview, Design Concepts, and Details protocol document
CO2	Carbon Dioxide	REDD	Reduced Emissions from Deforestation and Forest Degradation
USD	United States of America Dollars	UML	Unified Modelling Language
km	Kilometer	ha	Hectares
U.S.	United States of America	FFB	Fresh Fruit Brunches
BAU	Business As Usual	AGB	Above-Ground Biomass
RBL	Reduce Biodiversity Loss	GB	Government Expenditure
RCE	Reduce Carbon Emissions	PES	Payment for Ecosystem Services

ODD Protocol

Purpose

The purpose of the model is to explore the environmental and economic dynamics and relationships between investors (banks), palm oil companies, government and the environment in a SES representing the regions of Sumatra, Kalimantan and Papua in Indonesia.

Entities, state variables and scales

Agents: Firms, banks, government.

Patches: Land-covers.

See main paper for a detailed description of agents and patches. Figure 1 (main paper) shows a UML Class Diagram describing the model entities in detail.

Process Overview and Scheduling

The following is the list of the model processes taking place every time step, which are described in detail in the main paper: (i) compute CPO demand; (ii) banks compute credit lending; (iii) firms compute finance; (iv) banks compute credit lending; (v) firms compute resource extraction; (v) firms compute CPO price and sales; (vi) firms compute credit repayment; (vii) firms compute business expansion; (viii) patches compute age and resource extraction; (ix) patches compute indicators; (x) government computes policies.

Design Concepts

Adaptation

Firms adapt to the environment, for instance by selecting the most suitable areas for CPO production or the right time to harvest FFB based on plantation age; firms' sales vary based on their CPO prices; firms borrow credits based on their own particular financial situation; firms are forced to carry out certain processes (e.g. invest in technological development) based on government policies.

Objectives

The objective of banks and firms, as profit-seeking agents, are to increase their own revenues, unless otherwise stated by government policies under different scenarios (see 'Data calibration and scenarios' below). The objective of the government is to implement conservation strategies in order to enhance environmental sustainability.

Sensing

Firms consider patches' state variables, such as the type of land cover or biodiversity, at the time of selecting the most suitable sites to create new oil palm plantations.

Interaction

Firms interact indirectly with each other during CPO selling processes, as well as for selecting the most suitable areas to create new oil palm plantations (scenario dependant).

Collectives

The government represents all the local, regional, national and international public bodies implementing conservation measures in Indonesia; the bank represents all the international banks lending credits to oil palm companies in Indonesia.

Observation

Different environmental and economic indicators are computed to examine the sustainability of the SES (see Results in main text).

Initialization

The landscape is initialized to a random distribution of the land-covers. The primary, secondary, and forest-category patch parameters are initialized considering the total per cent values of land currently covered by each layer in Indonesia. Initial biodiversity and AGB values are allocated based on the type of primary, secondary and forest land covers; biodiversity is also set based on the production- and conservation-potential value parameters. Firms are randomly assigned one oil palm plantation each, and have 0 initial deposit account. CPO demand, inflation and price are initialized at the corresponding historical value in 2010. New protected areas, restored land, opportunity cost, credit (C) and government expenditure (GB) have 0 initial values.

Calculation method for conservation potential values (CPV)

Biodiversity in our model varies with the type of LUC taking place in each land-cover. Hence, the calculation of biodiversity values is based on three factors (i.e. partial conservation-value) affecting the conservation potential value per patch;

namely (i) the

initial land-cover at t, i.e. the type of land-cover before LUC takes place in each patch , (ii) the (final) land-cover at t+ 1, and (iii) the type of LUC from t to t + 1 (see 'Patches compute indicators' section in 'Submodels' for more information). The biodiversity value of each land-cover each time step (CV) is the result of multiplying the biodiversity value at t-1 by the resulting value from multiplying the three partial-conservation potential values (i.e. i, ii and iii) (see equation [1] below).

$$CV = CPV(t) \cdot CPV(t+1) \cdot CPV\ (LUC) \qquad [1]$$

Calculation method for changes in AGB values

Similarly to conservation-potential – yet following a different rationale – variation of above-ground biomass (AGB) values in our model is based on the impact of LUC in above-ground vegetated areas. AGB changes are driven only by the type of LUC occurring in each patch, not also by values at t and t+1 like biodiversity does; this is due to biodiversity in our model being a more complex variable (environmental asset) compared to AGB, thus being also affected by the type of land-cover prior and after LUC 1 (see 'Patches compute indicators' section in 'Submodels' for more information).

Input Data

See Table S2 below for information about the empirical input data used during both scenario setup (initialization) and as time series input for the different model entities.

Table S2: Entities included in the model, their state variables, units and values, dataset, and whether the variable is set during initialization (I) and/or time series input (TS).

Entity	State variable	Description	Variable type	Value	Dataset type	Dataset source	Set during I or TS
patches (land-covers)	primary-land-cover	Type of primary land cover	string (14 types)	see dataset	External dataset	OECD, 2016	I
	secondary-land-cover	Type of secondary land cover	String (3 types)	protected; plantation; semi-natural	External dataset	OECD, 2016	I
	forest-category	Type of forest category	string (5 types); only for protected and semi-natural	lowland; montane; heath; peat swamp' freshwater swamp	Literature data + Expert Knowledge	Budiharta et al. (2014)	I
	FFB	Stock of Fresh Fruit Bunches (FBB), used to produce CPO.	numeric	see data	Literature data + Expert Knowledge	Wilmar (2017)	I
	FFB-growth-rate	FFB growth function	numeric	0-1	Literature data + Expert Knowledge	Wilmar (2017)	TS
	oil-palm-age	Age of oil palm trees (only for oil palm plantation patches)	numeric	0-25	Literature data	Wilmar (2017)	I + TS

production-potential	Land suitability for new oil palm plantations	String (4 grades)	low; moderate; high; very high	Literature data + Expert Knowledge	Gingold et al. (2012)	TS
AGB	Vegetation cover (in tons patch-1).	numeric	see Dataset Source	Literature data + Expert Knowledge	Budiharta et al. (2014)	I + TS
AGB-change-function	Rate at which AGB values change.	numeric	see Table S4	Expert Knowledge	N/A*	TS
carbon	Carbon stock (in t).	numeric	Convert AGB into C	External dataset	Krisnawati et al. (2015)	I + TS
CO_2	CO_2 stock (converted from carbon).	numeric	1ton C = 3.67 ton CO_2	Expert Knowledge	N/A	TS
degradation-category	Grade of environmental degradation, used for degraded land restoration by the government	numeric (4 grades), in AGB remaining	light (61-100%); moderate (41-60%); high (21-40%); critical (0-20%)	Literature data + Expert Knowledge	Budiharta et al. (2014)	TS
biodiversity	Biodiversity value.	numeric	0-1	External dataset	Wilson et al. (2010)	I
biod-change-function	Function computing changes on biodiversity values	numeric	See Tables S2-S3 and equations [8]-[9]	Expert Knowledge		
conservation-potential	Land suitability for being protected by the government	String (4 grades)	See Tables S2-S3	Expert Knowledge	N/A	TS

* N/A refers to those parameters whose values change due to internal model dynamics.

bank	credit (C)	Loans lent by the bank to firms	numeric	Between 733.67 and C = 86.126x – 172,457 (‘x’ = model time step) (USD million)	External dataset	Forest and Finance (2016)	TS
	interest-rate	Interest on credits, set by banks to make revenues.	numeric	0.02	External dataset	World Bank (2016)	I + TS
	transaction-account	Monetary capital accumulated by banks (difference between sum of credits lent and credits + interests repaid by firms to the bank)	numeric	0-?†	N/A	N/A	TS
firms	CPO	Stock of CPO produced by firms	numeric	0-?	External dataset + Expert Knowledge	Indonesia Investments (2016)	I + TS
	CPO-price	CPO price set by firms	numeric	228-700 (USD)	External dataset	Investing (2017)	I+TS
	firm-deposit-account	Monetary capital accumulated by firms	numeric	?	External dataset + Expert Knowledge	Indonesia Investments (2016)	I+TS
	debt	Monetary capital owed by each firm to the bank.	numeric	?	N/A	N/A	TS

† All question marks in this table refer to any possible positive numeric value (i.e. < 0).

	tech-development	Monetary capital invested by firms on technological development	numeric	0-100%	Expert Knowledge	N/A	TS
	other-expenses	Monthly expenditure of firms regarding wages‡ and other expenses related to CPO production.	numeric	0-100%	Expert Knowledge	N/A	TS
government	budget	Government budget (expenditure) allocated for conservation purposes.	numeric	500-1250 (USD million)	Literature data	(Budiharta et al., 2014)	I
	policy-1	Firms to prioritize increasing production efficiency in existing plantations, instead of expanding plantations	string	N/A	Expert knowledge	N/A	TS
	policy-2	Firms to create new plantations solely in degraded lands.	string	N/A	Expert knowledge	N/A	TS
	policy-3	Restoration of degraded land.	string	N/A	Expert knowledge	N/A	TS
	policy-4	Enlargement of the protected area network	string	N/A	Expert knowledge	N/A	TS

‡ Note that neither employees/households are not agents in this model, but functions affecting the deposit accounts of firms by reducing and increasing their monetary capital, thus simulating wage payments and gains from CPO sales, respectively.

global	opportunity-cost	The loss of potential future profits from CPO production due to land protection.	numeric	?	N/A	N/A	I + TS
	CPO-demand	Function showing the overall global CPO demand.	discrete number	17-40 (million tons)	External dataset	Gran View Research (2017)	I
	carbon-price	Price of one ton of carbon	discrete number	?	Literature data	Maulidia (2014)	I

Submodels

Scenario selection

The user selects the scenario to be explored in each simulation (see main paper).

Compute CPO demand

CPO demand is computed and updated every time step based on input data (see Table S2). The overall demand is disaggregated at the firm level, thus each firm computing its own CPO demand every time step. Here, the firm offering the lowest price is placed at the top of a right-skewed distribution (showing price on the X Axis and demand in the Y axis), thereby being the one selling higher CPO quantities. The price corresponding to the amount of CPO sold by each firm every time step is allocated to the firm's deposit account.

Banks compute credit lending

Firms borrow credits from banks in a yearly basis, regardless of the profits obtained the previous year, in order to cover the operating costs of CPO production for the coming year, i.e. wages, daily expenditures. The amount borrowed by each firm is dependant to the particular financial situation of each firm.

Firms compute finance

Firms calculate the mismatch existing between the previous and current year regarding costs of producing CPO. If additional capital needed, firms borrow further credits from the bank until the amount needed is reached.

Banks compute credit lending

Banks lend credits to firms, thus helping the latter to meet the above-noted financial mismatches.

Firms compute resource extraction

Every month, firms harvest fresh fruit bunches (FFB) from their owned plantations. Those plantations with trees in their peak production (7-18 years) are prioritized; if each firm is able to meet its corresponding CPO demand by just harvesting FFB from peak production plantations, no further harvesting is needed. Otherwise, firms extract FFB from plantations between 19-25 years, followed by those under 3-8 years. The amount of resources to be extracted by each firm is given by:

$$Re = Y \cdot C \qquad [2]$$

Where *Re* refers to the *amount of resources* extracted by each firm every time step, Y is the *output* (in tons) needed to meet the CPO demand, and C is a *biomass conversion factor*.

Firms compute CPO price and sales

Firms set a price (P), based on a combination of historical data (*hp*) and predicted data (*pp*), as well as other firms' prices (*op*). In particular, firms calculate the average price value among these three factors, each of which receives a different weight, being historical data (α = 50%) the most relevant, followed by predicted (β = 30%) and other firms' prices (γ = 20%). See '(i) Compute CPO demand above' for further information on prices.

$$P = (\alpha)hp \cdot (\beta)pp \cdot (\gamma)op \qquad [3]$$

Firms compute credit repayment

If firms have no sufficient monetary capital to cover the monthly credit repayment to the bank, further credits are borrowed from the bank – summing up to double the amount of the monthly debt owed by the firm. Otherwise, firms pay back the monthly debt, with interests, with their current monetary capital. Note that, because the bank agent in our model represents all the financial entities lending credits to palm oil companies in Indonesia, firms unable to repay their debt would borrow credits from a second bank in order to cover the debt with the prior bank (yet in our model this occurs within the same bank).

Firms compute business expansion

Firms expand their business, i.e. create one new firm elsewhere in the model, if their current income is double compared to the previous year; note that, as explained in the calibration process (see ‘Data evaluation’ below), firms create new plantations, yet no new firms, as part of the process of business expansion. The selection of suitable areas for new firms is based upon the land covers’ production potential (*PP*), conservation potential (*CP*) and land availability (*LA*), i.e. with no other firms there. PP and CP determine the environmental and palm oil production yield values of each land-cover, respectively. Each land-cover computes one CP value – based on biodiversity and carbon stocks – and one PP value – based on palm oil yield – every time step by following a matrix approach, which means that not only the values from the actual patch are considered, but also the values from the surrounding patches (i.e. buffer zone). In particular, PP and CP values are classified as ‘very high’ (0.75-1), ‘high’ (0.5-0.75), ‘moderate’ (0.25-0.5) or ‘low’ (0-0.25) – given by expert-based qualitative conversion probability assignments. Each patch therefore computes the average value (between 0-1) every time step regarding its PP, CP and LA values, as well as the ones from the surrounding patches (note that, while PP and CP show values within 0 and 1, LA is a binomial parameter showing 1 for available land-covers and 0 for non-available). This final value computed by each patch is known as the conversion probability value. The land-cover with the highest conversion probability value is the one finally selected by the firm to have the new plantation. Moreover, CP and PP parameters regarding each land-cover are given a unique weight varying from scenario to scenario. Thus, the final conversion (C) to plantation value for each land cover is given by:

$$BAU \rightarrow C = (\alpha)PP \cdot (\beta)CP \cdot LA\,; \quad \alpha = 1, \beta = 0.1 \qquad [4]$$

$$RBL \rightarrow C = (\alpha)PP \cdot (\beta)CP \cdot LA\,; \quad \alpha = 0.1, \beta = 1 \qquad [5]$$

$$RCE \rightarrow C = (\alpha)PP \cdot (\beta)CP \cdot LA\,; \quad \alpha = 0.3, \beta = 0.7 \qquad [6]$$

$$SF \rightarrow C = (\alpha)PP \cdot (\beta)CP \cdot LA\,; \qquad \alpha = 0.7, \beta = 0.7 \qquad [7]$$

Banks compute credit lending

If firms do not have enough monetary capital for business expansion, they borrow credits from the bank equal to the amount needed to cover such expenses, i.e. one tenth of the monetary capital from five years ago.

Patches compute age and resource extraction

Each oil palm plantation land-cover computes an age function, being 0 the starting age and 25 the maximum age (i.e. maximum commercial lifespan, after which the trees are cut down by firms). One time step corresponds to one month, thus after 12 time steps each oil palm patch is one year older than the previous time step. Furthermore, each oil palm land-cover has a FFB stock, which increases or decreases based on both growth and extracting forces affecting it; while the extraction forces are given by the amount of FFB needed by the firm owning this patch to meet CPO demand, the FFB growth rate is given by a resource growback function.

Patches compute indicators

Each patch, regardless of its land-cover type, computes both biodiversity (B) and carbon stock (CS) functions (the latter calculated from the amount of AGB). The following rationale refers to biodiversity, yet it can be applied to CS also:

Biodiversity values for each land-cover type varies and is updated every time step following equations [8] and [9] below, in which $B(t)$ decreases/increases with the proportion of habitat destroyed/restored (DR) in each patch and in its surrounding (neighbour) patches (DR_n), based on the type of LUC (see Figure S1 for a conceptual illustration). DR_n refers to those target-neighbours (DR_{tn}) that are protected, semi-natural or palm oil plantations; thus, each patch only calculates the average DR value ($\overline{DR_{tn}}$) regarding its target-neighbours. If no target-neighbours present, the patch increases its radius until any target-neighbours become present. The aim of including

DR_n in equation [9] is to integrate the impact on biodiversity of habitat destruction and restoration taking place in the surrounding areas.

$$B(t) = B(t-1) \cdot (DR \cdot DR_n) \quad [8]$$

$$DR_n = \overline{DR_{tn}} \quad [9]$$

Calculation method for habitat destruction-restoration (DR) values

Computation of *DR-values* per patch is based on three factors: the effect on biodiversity of (i) the type of LUC from t to t + 1 (see Table S3 for the values), (ii) the initial land-use at t (Table S2), and (iii) the (final) land-use at t+ 1 (see Table S2 and S4 for the values). As an example, one semi-natural patch with high biodiversity and one oil palm plantation with low biodiversity – both being converted to protected areas – will show different biodiversity values during the entire LUC process until they become fully protected. This is due to these two patches having different initial biodiversity states based on their initial (t) land-use. Similarly, the final land-use (t+1) and the type of LUC would affect both biodiversity values. Figure S1 below shows an illustration for DR calculation.

DR_{tn} semi-natural	DR_{tn} semi-natural	DR_{tn} protected area
DR_{tn} protected area	$\boldsymbol{DR}$	DR_{tn} oil palm
DR_{tn} protected area	DR_{tn} oil palm	DR_{tn} oil palm

Figure S1: Representation of nine NetLogo patches in our model. The patch in the center computes its own *DR-value* and the average *DR-value* from their surrounding target-neighbours (DR_n).

Table S3: Initial (t) and final (t+1) partial-conservation potential values (CPV).

Primary land-cover classes	CPV (t) and (t+1)
protected area (PA)	1.25
available semi-natural (SN)	1
oil-palm plantation (OPP)	0.5
other land-cover (OLC)	N/A

High values refer to high conservation potential value. Note that other land-covers, yet represented in the model, do not affect biodiversity (nor AGB values below).

Table S4: Partial-conservation potential values (CPV) for each LUC type.

Type of LUC	CPV (LUC)
PA→PA	2
OPP→PA	1.85
SN→PA	1.3
OPP→SN	1.25
SN→SN	1
PA→SN	0.70
SN→OPP	0.5
PA→OPP	0.25
OPP→OPP	0.01

Partial-conservation potential values range from 0 (low potential for protection) to 2 (high potential). This range (0-2) is larger than the one from Table S2 HQ range (0.75-1.25), since we give a higher weight to the type of LUC – compared to the initial and final land-cover states – in terms of affecting biodiversity in our model.

Table S5: AGB values calculation method.

Type of LUC	AGB multiplier
OPP→PA	1.50
OPP→SN	1.45
SN→ PA	1.30
SN→ A PA	1.10
PA→PA	1.10
SN→SN	1
PA→ SN	0.97
SN→SN	0.95
SN→ OPP	0.85
PA→ OPP	0.50

Government computes policies

The government computes different policies and invests public money to enhance conservation of biodiversity and decrease carbon emissions/increase carbon stocks. The selection of these policies varies from scenario to scenario, thus affecting firms' decision-making and model outcomes. The policies implemented by the government are aimed at:

(i) increasing CPO production efficiency on existing plantations by investing in technological development; and/or

(ii) reducing the number of new oil palm plantations created in areas with high biodiversity and/or carbon stocks, thus prioritizing the use of degraded lands for this purpose.

Similarly, the government can allocate part of its budget (GB) for:

(iii) restoring degraded land; and/or
(iv) increase the number of protected areas.

The government budget is reduced every time new areas are protected or restored, thus representing compensation payments for those companies managing commercial plantations in restored or protected areas. The selection of those land-covers to be restored is based on the grade of degradation in descending order; thus we follow Budiharta et al. (2014) regarding the maximum AGB (in per cent values) that needs to be present in each land-cover in order to be considered ‘critically degraded’ (0%-20% AGB remaining), ‘highly degraded’ (21%-40% AGB remaining), ‘moderately degraded’ (41%-60% AGB remaining) or ‘lightly degraded’ (61%-100% AGB remaining).Similarly, areas to be protected are selected based upon the conservation potential of each land-cover – which establishes the environmental value of each land-cover and, therefore, the potential to be (un)protected – going from higher to lower conservation potential. Finally, the financial opportunity cost of CPO production is calculated at the national level based on the revenue foregone from CPO production as a consequence of restoration and protected area creation.

Scenarios

Table S5 shows the parameters, target values and data sources selected for each scenario. The top row shows the parameters used to setup each of the four different scenarios (left column), which were selected based on expert opinion (explained below). The values of the parameters on the top row change from scenario to scenario, while the last row shows the sources from which the different scenario values were obtained. ‘Bank Credits (C)’ and ‘Government Budget (GB)’on the left part of top row are the economic parameters financing the rest of parameters (from the top row). The ranges of values for all parameters include the possible values that agents can compute in each modelling time step.

Table S6: Parameters, target values and data sources for each scenario. Note that ‘l’ and ‘h’ letters, under RBL and RCE scenario names, refer to ‘low’ and ‘high’, respectively. The letter placed in first position corresponds to Government Budget (GB), whereas the second position corresponds to Credits (C). As an example, RBL_lh refers to ‘Reduce Biodiversity Loss’ scenario with ‘low’ GB and ‘high’ C.

	Bank Credits (C) (in USD million)	**Government Budget (GB)** (in USD million)	**Technological Development** (C and GB funded)	**Oil Palm Plantation Expansion** (BC and GB funded)	**Protected Areas** (GB-funded)	**Restoration** (GB-funded)
Business As Usual **(BAU)**	Between 733.67 and C = 86.126x – 172,457 (‘x’ = model time step)	Maximum of 500	No	From most productive to least productive areas, regardless of biodiversity and carbon stocks.	Increase in 0-3%	No
Reduce Biodiversity Loss **(RBL)**	**RBL_hh** and **RBL_lh** = between 1088.045 and 1442.42. **RBL_hl** and **RBL_ll** = between 733.67 and 1088.045	**RBL_hh** and **RBL_hl** = between 875 and 1250 **RBL_lh** and **RBL_ll**= between 500 and 875	Yes (0 - 7.5%)	From degraded forests, through agricultural lands and secondary forests, to swamp forests.	Increase in 7-10%	Yes – in moderately degraded forests
Reduce Carbon Emissions **(RCE)**	**RCE_hh** and **RCE_lh** = between 1088.045 and 1442.42. **RCE_hl** and **RCE_ll** = between 733.67 and 1088.045	**RCE_hh** and **RCE_hl** = between 875 and 1250 **RCE_lh** and **RCE_ll** = between 500 and 875	Yes (0 - 7.5%)	From degraded peatlands, through agricultural lands and secondary peatlands, to primary forests.	Increase in 3-5%	Yes – in highly degraded lowland forests
Sustainable Futures **(SF)**	Between 733.67 and C = 86.126x – 172,457	Between 500 and 1250	Yes (7.5 - 15%)	From degraded lands with high production potential, through agricultural lands and secondary forests, to least productive degraded lands.	Increase in 3-7%	Yes – in both highly and moderately degraded forests
Scenario target value sources	Forest and Finance (2016)	Budiharta et al. (2014)	Authors	Budiharta et al. (2014)	Murdiyarso et al. (2011); World Bank (2014)	Budiharta et al. (2014)

More specifically, 'Technological Development' shows the maximum and minimum (per cent) monetary value that each firm can invest, on a monthly basis, in increasing production efficiency in existing palm oil cultivations. Both 'Oil Palm Plantation Expansion' and 'Restoration' describe the type of land cover prioritized, in descending order, regarding the creation of new oil palm plantations and for restoring degraded areas, respectively. Note that the prioritization of moderately degraded forests for restoration under RBL is based on forests under this condition having higher potential for biodiversity compared to carbon sequestration (Budiharta et al., 2014). Here, non-native commercial tree species could be replaced with highly diverse native species. On the contrary, highly degraded forests have higher potential for carbon sequestration compared to biodiversity conservation (Budiharta et al., 2014). 'Protected Areas' shows the maximum and minimum amount of land (in % values) to be protected during the entire simulation period (going from higher to lower conservation potential areas); RBL values are higher than RCE due to area protection being a strategy more focused on improving biodiversity outcomes rather than climate change mitigation (Murdiyarso et al., 2011).

Expert opinion process

Expert opinion was used to select the scenarios – including the parameters and parameter (target) values for each scenario – as well as the main factors/variables to be included in the model (based on the particular context of the study area). The expert opinion process followed a 'focus groups' approach (Kitzinger, 1994; Morgan, 1998; Gill *et al.*, 2008), where a group of discussion was organized during one week, in order to provide a deep understanding of the main socio-economic and environmental factors driving SES (un)sustainability in Indonesia. Expertise was sought from ten scientists from different fields, including ecology, agricultural sciences, ecological economics, environmental governance, and sustainability science. More specifically, the first day consisted on providing an overview of the research topic and the case-study area, as well as the goal of the research work. The second day consisted on asking open-ended questions to the experts, as well as collecting information and data sources from them about the main SES (un)sustainability issues currently taking place in Indonesia. The main issues were focused on the current economic-conservation dichotomy present in

Indonesia, the highly dependency of the palm oil industry on external financial institutions, and the potential conservation policies being implemented to counterbalance the negative environmental impacts exerted by such scenario. The last three days consisted on specific and sound discussions, including end-questions to experts on what particular scenarios (including target values) and key factors/variables should be integrated in the model for analysing the current SES (un)sustainability context present in Indonesia.

Model calibration

Model calibration was used to determine the values for Credits (C), Government Budget (GB) and number of firm agents[4] modelled under the BAU scenario; note that the calibration results were thereafter used to set and optimize the other three scenarios (explained at the end of this section). The selection of these three parameters for model calibration is due to these being the main drivers of model outcomes. More specifically, the importance of Credits (C) parameter lies in its direct effect on CPO production, biodiversity and CO_2 emissions, as well as other sustainability indicators, through technological development and oil palm plantation expansion; similarly, GB drives land conversion of protected and restored areas, thus affecting biodiversity and CO_2 emission indicators. Moreover, the importance of calibrating BC and GB lies on the fact that these constitute the main two parameters used to set the Power Imbalance values (see Results).

In brief, a direct calibration was performed for BC, while an inverse calibration was performed for GB and number of firm agents; thus, while the historic data available on credits borrowed by palm oil companies (i.e. BC) was fitted to model outcomes, the lack of data for government budget (i.e. GB) and the number of firms forced us to use alternative historic data from other indicators in order to fit model outcomes. In

[4] The number of government and bank agents was not calibrated as only one of each type was modelled (government and bank agents are conceptual representations, yet using empirical data, of international and national entities involved in credit lending and conservation).

particular, the expansion/contraction of the protected area network and CPO production were used to calibrate GB and firm agents, respectively.

First, an inverse calibration was performed to select the number of firm agents in the simulation, due to lack of available data on the number of oil palm companies present in Indonesia. Thus, our calibration process consisted on using data on palm oil production (2008-2016) (see Table S2) to optimize the number of firm agents necessary to fit CPO production in our model with historic data. While the initial idea was each firm agent to represent a homogeneous group of mills, refineries and farmers, this assumption overshoot the number of firms in the simulation and thus enhanced meteoric and unrealistic CPO production trends (see 'non-calibrated' curve, Figure S2), compared to historic data (see 'historic data', Figure S2). Therefore, we considered that firms would rather represent both national and international investment groups (i.e. forest-risk groups) financing CPO production in Indonesia; examples of these groups are shown in Forest and Finance (2016). As a result, the initial number of firms was reduced to 16, which helped aligning CPO production in our simulations with historic data (see 'calibrated' curve, Figure S2). In brief, the calibration process enabled us to realize that the problem was conceptual (in terms of the idea/concept of a 'firm'), rather than the number of firms itself. Note that, despite the number of firm agents being a fixed parameter, the number of palm oil plantations changes over the simulation period.

Regarding Credits (BC) parameter, a direct calibration was performed through available historic data from the Forest and Finance (2016) web tool. This dataset is part of a growing campaign targeting investors and financial institutions that finance companies implicated in tropical deforestation in the Asia Pacific region. Various field search functions within this tool permit comprehensive assessments into how companies linked to rainforest destruction are financed by the world's biggest banks. The tool shows the impact on deforestation of different financial assets; while initially all of them were selected (i.e. bond issuances, bondholding, corporate loans, revolving credit facilities, share issuances, shareholding) these included speculative and other types of investments that are not directly involved in the processes of FFB harvesting and CPO production themselves. As a result, simulation results for Credits showed lower trends (see 'Simulated results' curve, Figure S3) compared to historic data (see 'All financial assets', Figure S3). Moreover, the over inclusion of financial assets enhanced unrealistic

CPO production values. Therefore, we decided to solely consider ‘corporate loans’ and ‘revolving credit facilities’ as historic data – among all financial assets – as these are directly used by oil palm companies for CPO production. Thereafter, the alignment between model results and historic data was improved (see ‘Corporate loans and revolving credit facilities’ curve, Figure S3).

The last parameter to be (inversely) calibrated was Government Budget (GB). The lack of available historic data on government investments for conservation purposes was substituted by using literature data sources, mainly from Budiharta et al. (2014). Thus, we tested the impact of different GB values used in Budiharta et al. (2014) on protected area expansion, which is one of the two processes (together with restoration of degraded land) driven by GB investments in our model. In particular, GB values varying between a minimum (500 USD million) and maximum (1250 USD million) values were integrated in our model to explore their effect on protected area expansion. Initially, the number of protected areas simulated (see ‘non-calibrated’ curve, Figure S4) was not aligned with historic data (see ‘historic data’ curve, Figure S4), since it would only simulate non-dynamic steady state trends. By integrating one random variable we increased stochasticity in our model, thus enhancing GB value oscillation between the above-noted minimum and maximum GB values under RBL and RCE scenarios (see ‘calibrated’ curve, Figure S4).

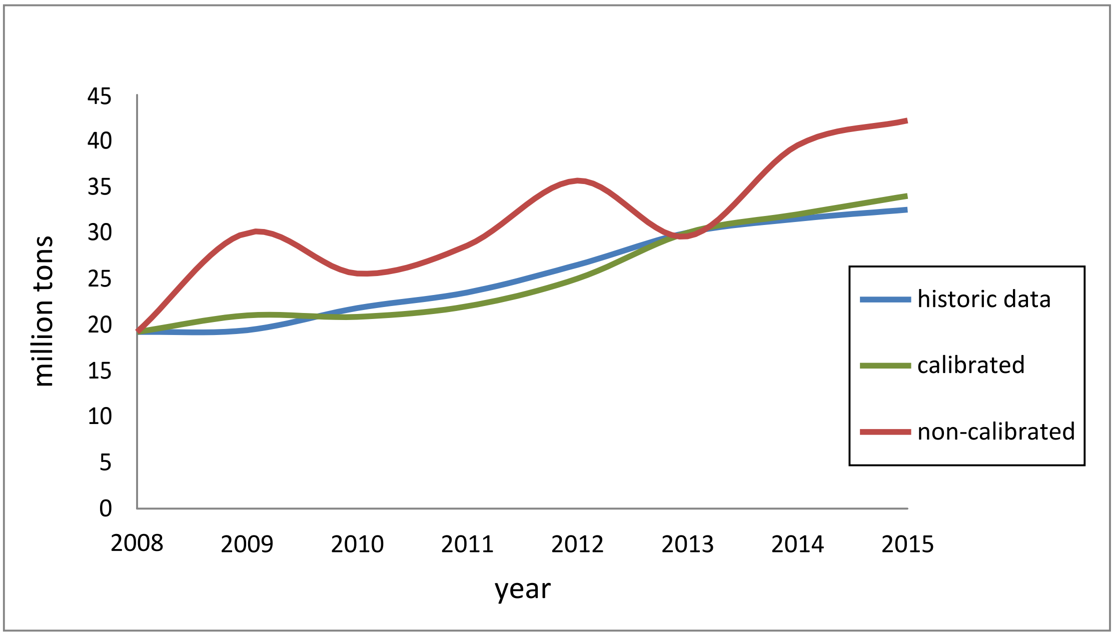

Figure S2: Historic, non-calibrated and calibrated trends for CPO production parameter, which is used to indirectly calibrate the number of firms.

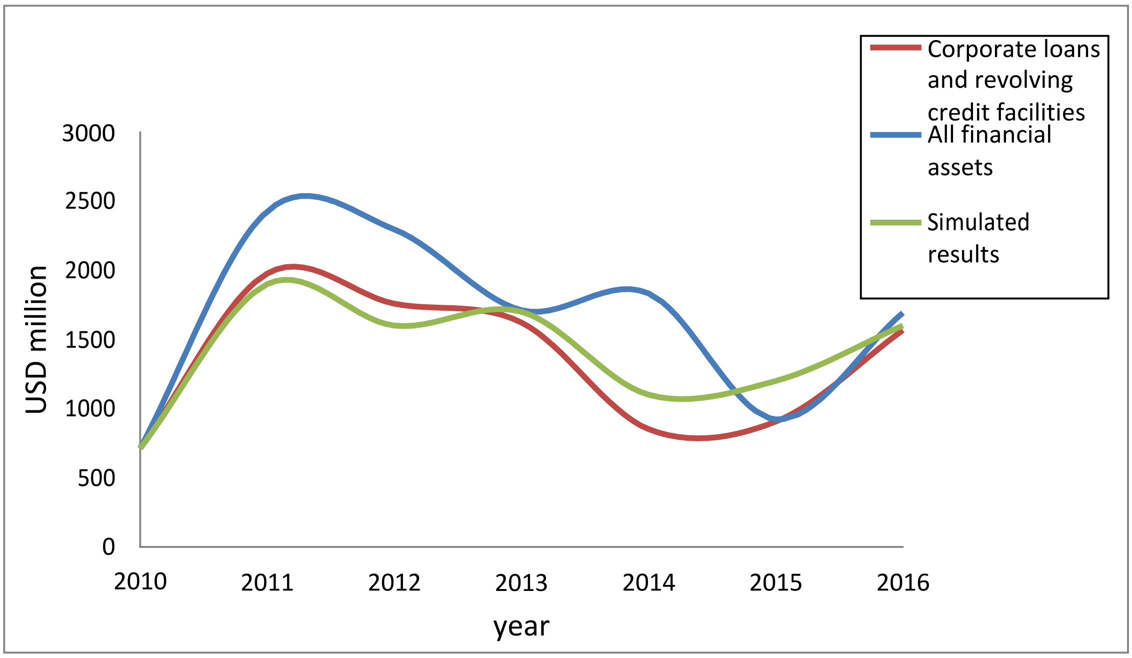

Figure S3. Corporate loans and revolving credit facilities (i.e. calibrated), all financial assets and simulated results regarding the direct calibration of Credits (C).

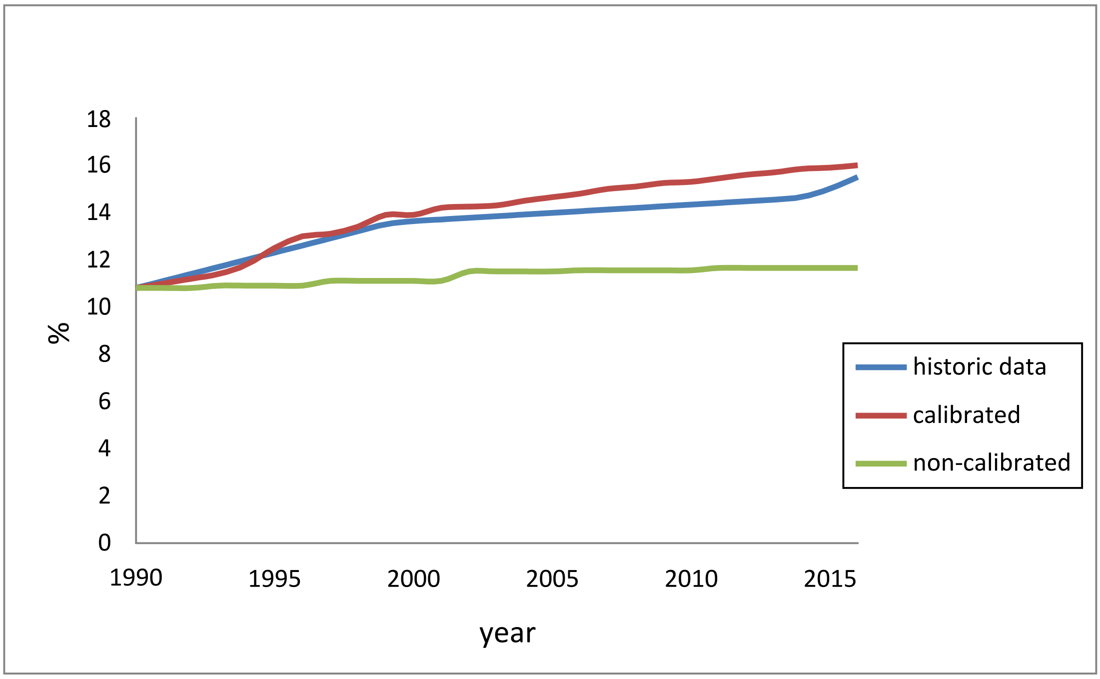

Figure S4. Historic, non-calibrated and calibrated trends for protected areas parameter.

Calculation of Power Imbalance values

This section describes the calculation and context of the Power Imbalance values from Figure 7 in the main paper. Power Imbalance values are calculated through a simple BC/GB function that states the proportion of total credits available (BC) to the government budget for conservation (GB). Power Imbalance values range from high (on the right- hand side of the *x-axis* in both heatmaps, Figure 7) – where the amount of BC available for CPO production is considerably higher than GB – to low Power Imbalance values (on the left-hand side of the *x-axis* in both heatmaps, Figure 7) – where GB and BC show similar values, or even GB being higher than BC. Note that, placing BC as a numerator and GB as a denominator in the BC/GB function, favors economic development over conservation. This decision was made following Hill *et al*. (2015a), who argue that current economic forces driving land clearing for production in tropical countries are stronger than conservation forces driving land protection and restoration. Hence, high GB values in the model can only but equilibrate the power distribution between banks (economic forces) and conservation governance (conservation forces), yet never shift it towards favouring conservation over economic – due to the current BAU reality analysed in Hill *et al*. (2015a).

References

Budiharta, S., *et al*. (2014). Restoring degraded tropical forests for carbon and biodiversity. *Environmental Research Letters*.

Forest and Finance. (2016). Rainforest Action Network (RAN), TuK INDONESIA, and Profundo [online]. Available at: http://forestsandfinance.org/> [Accessed Apr 2017] .

Gill, P., Stewart, K., Tresure, E. and Chadwick, B. (2008). Methods of data collection in qualitative research: interviews and focus groups. *The British Dental Journal*, 204, pp. 291-295.

Gingold, B., *et al*. (2012). How to identify degraded land for sustainable palm oil in Indonesia. Working Paper, World Resources Institute and Sekala, Washington D.C [online]. Available at: <http://data.wri.org/POTICO/English_how_to_identify_degraded_land_for_sustainable_palm_oil_in_indonesia.pdf. Cited 28 June 2017> [Accessed 22 Mar 2018].

Gran View Research. (2017). Research Reports by Industry – Renewable Chemicals [online]. Available at: <http://www.grandviewresearch.com/filters?search=palm+oil> [Accessed July 2017] .

Indonesia Investments. (2016). Palm Oil In Indonesia – Indonesian CPO Production & Export [online]. Available at: <https://www.indonesia-investments.com/business/commodities/palm-oil/item166.Cited 16 June 2017> [Accessed July 2017] .

Investing. (2017). Crude Palm Oil Futures [online]. Available at: <https://uk.investing.com/commodities/crude-palm-oil. Cited 16 June 2017> [Accessed July 2017] .

Kitzinger, J. (1994). The methodology of focus groups: the importance of interaction between research participants. *Social Health Illn*, 16, pp. 103-121.

Krisnawati, H., Imanuddin, R., Adinugroho, W.C. and Hutabarat, S. (2015). Standard Methods for Estimating Greenhouse Gas Emissions from Forests and Peatlands in Indonesia (Version 2). *Research, Development and Innovation Agency of the Ministry of Environment and Forestry*. Bogor, Indonesia.

Maulidia, M. (2014). Carbon tax for Indonesia: Time to act now. The Jakarta Post. 29 April 2014. Available at: <http://www.thejakartapost.com/news/2014/04/29/carbon-tax-indonesia-time-act-now.html>. [Accessed June 2017].

Morgan, D.L. (1998). *The focus group guide book*. London: Sage Publications.

Murdiyarso, D., Dewi, S., Lawrence, D. and Seymour, F. (2011). *Indonesia's Forest Moratorium: A Stepping Stone to Better Forest Governance?* Bogor: Center for International Forestry Research.

OECD – Organisation for Economic Co-operation and Development(2016). OECD Economic Surveys: Indonesia [online]. Available at:<https://www.oecd.org/eco/surveys/indonesia-2016-OECD-economic-survey-overview-english.pdf> [Accessed July 2017].

Wilmar (2017). Tropical Oils Plantations [online]. Available at: <http://www.wilmar-international.com/our-business/tropical-oils/plantations/harvesting-oil-palm-yield/> [Accessed June 2017].

Wilson, K.A., *et al*. (2010). Conserving biodiversity in production landscapes. *Ecol. Appl.*, 20, pp. 1721–1732.

World Bank (2016). International Monetary Fund, International Financial Statistics and data files. Lending interest rate (%) [online]. Available at: http://data.worldbank.org/indicator/FR.INR.LEND. [Accessed July 2017] .