Sustainable Futures in Tropical Landscapes: An Integrated Agent-Based Modelling Approach

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Abstract. Ensuring the well-being of current and future generations within the limits of natural systems require solutions regarding three pressing concerns for global sustainability: climate change mitigation, biodiversity conservation, and food production. This trade-off is being addressed by different strategies across the globle. For instance, environmetal governance in the Wet Tropics, Australia, has progressed from a single-purpose focus – logging and land clearing for agriculture – towards a multifunctional landscape management. In this paper, we ask: which governance framework and combination of socio-economic factors could help decoupling environmental pressures from economic growth in tropical regions? We build an integrated and spatially explicit Agent-based Model (ABM), under a land-sharing/land-sparing framework, to explore the extent to which future land-use scenarios could affect sustainability in the Wet Tropics of Queensland, Australia. Our ABM incorporates Bayesian Belief Networks, GIS, empirical data and expert knowledge to study the impact of different landscape configurations on trade-offs of biodiversity and two ecosystem services (cabon sequestration and sugarcane production). Contrary to most tropical countries, simulation results show that Business As Asual helps increasing sustainability in the Wet Tropics. We analyse which combination of socio-economic and governance factors is driving these results, and explore potential pathways to improve sustainability in other tropical countries. Our model can be used to provide different policy making alternatives for targeting conservation priorities while supporting climate change mitigation and production management options.

1 Introduction

Humans now manage the majority of land on earth, with more and more land put over to agriculture, especially in tropical forests, which are declining. It is, therefore, no surprise that a debate about how to reconcile the needs of people and nature has resurfaced (Fenning, 2014). This question is particularly important in tropical regions, which face three main issues for global sustainability. First, future food demand is projected to increase by at least 70% by 2050 in response to growing levels of per capita consumption, shifts to animal-based diets, and increasing population (Godfray et al., 2010), thus improving agricultural productivity in the tropics is critical to meet this demand. Second is the need to reduce atmospheric concentrations of greenhouse gases to address climate change that is progressively affecting agriculture, coastal areas, human health, and many other sectors (UNFCCC, 2009). Third is biodiversity loss. The global biodiversity crisis has been well documented, with one-fifth of the world's assessed vertebrates being at imminent risk of extinction and many more less-understood species thought to be under similar threat (Hoffmann et al., 2010). In particular, land-use change (LUC), driven by the expansion and intensification of agriculture and plantations, is a main cause of biodiversity loss (Phalan et al., 2013).

Two broad strategies are often promoted to decouple economic growth from evironmental pressures at the landscape level: one intensifies production in one part of the landscape and strictly protects the reminder – land sparing (LSP) – while the other integrates production and protection in an agro-ecological matrix – land sharing (LSH) (Green et al., 2005). Despite the LSP vs. LSH framework being recognised as providing a useful structure for trade-offs between biodiversity conservation and agricultural yields (Green et al., 2005), literature in this field lacks of empirical modelling applications and case-study examples.

This paper presents an integrated ABM, built using NetLogo (Wilensky, 1999), that combines Geographic Information Systems (GIS), Bayesian Belief Networks (BBN), empirical data and expert knowledge to examine which governance and policitcal policy forces, represented by different land-use and landscape scenarios, could enhance sustainability in the Wet Tropics Natural Resource Management (NRM) Region, Queensland, Australia. In particular, the scenarios modelled explore the spatial and empirical impacts of different LUC (i.e. land preservation, land restoration and land development) on three different indicators: biodiversity, carbon sequestration and sugarcane production. The model is used to address three main questions; namely [a] which scenario (Business as Usual (BAU), LSP, or LSH) would increase landscape sustainability in the Wet Tropics NRM Region (i.e. enhance synergies between biodiversity and ES), [b] which particular combination of governance forces are driving these results; and [c] whether our results could be extrapolated to other tropical SES, thereby analyzing which landscape management approaches could enhance the long-term sustainability of tropical regions underdifferent social-economic contexts.

2 Methods

2.1 Case-study Area

The Wet Tropics NRM Region (Figure 1) is located in the North East of Queensland, Australia, and covers an area of 21,722km^2. It is the only region in the world to include two contrasting World Heritage Areas side by side: the Wet Tropics World Heritage Area (WTWHA) and the Great Barrier Reef. As one of the most biologically diverse areas in the world, forests in the Wet Tropics were recognised in 2010 as one of 35 international global biodiversity hotspots, with more than 1,500 endemic vascular plants and more than 70 per cent of its original (pristine) native vegetation lost or significantly degraded.

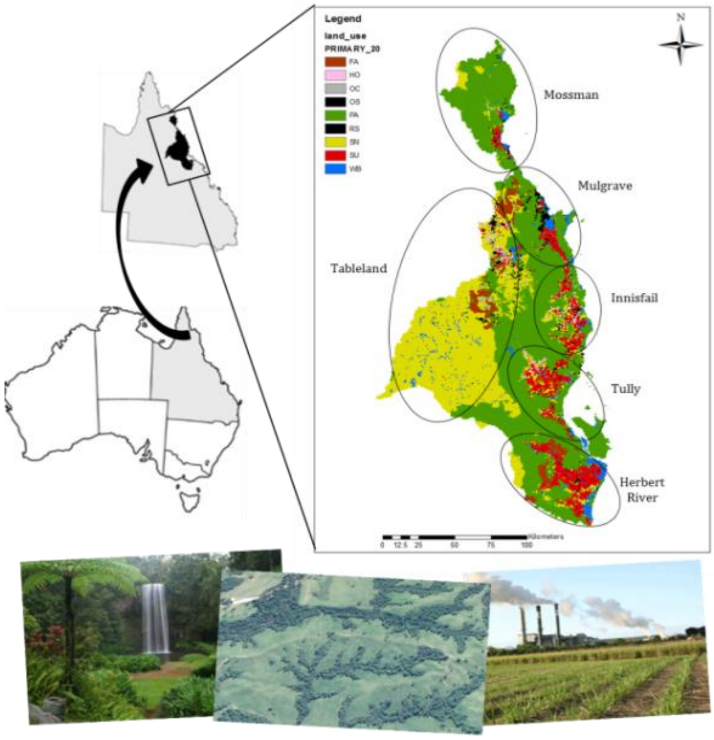


Fig. 1. Geographic location of the Wet Tropics NRM Region. Land-use legend: forestry areas (FA), horticulture (HO), other crops (OC), other services (OS), protected areas (PA), residential areas (RS), semi-natural areas (SN), sugarcane lands (SU) and water bodies (WB). Circled areas show the different sugarcane mill-areas present in the case-study area. The photographs on the bottom are local examples of the three primary grups of land-uses analysed; namely protected areas (left), semi-natural areas (center), and sugarcane lands (right).

2.2 Framework

Figure 2 shows the integrated methodological framework used to build the model, which combines BBN, GIS, empirical data and expert knowledge. Our methodological framework is adapted from the TRACE documentation from Grimm et al. (Grimm et al., 2011), using NetLogo as the ABM construction software. Literature review is performed to develop the research questions being addressed and the conceptual framework applied in our research study. ArcGIS and QGIS are used to import the baseline land-use map into NetLogo, as well as the rest of GIS layers used to set the LUC potentiality values. Published empirical data is computed at the patch level in those cases where GIS layers were not available. Finally, BBNs (see section below), which are built using the GeNIe BBN builder tool (GeNIe & SMILE, 1998) and completed using expert knowledge, provide the information to compute LUCs in our model and thus help to accommodate uncertainty as conditional probabilities. The BBN building process follows a logical framework adapted from the Australian Department of the Environment, Heritage and the Arts (DEWHA, 2010). Although the use of BBNs for modelling LUC is not new (Lynam et al., 2002; Bacon et al., 2002), examples of the incorporation of BBNs in spatial ABMs are scarce and confined to utility maximization (Kocabas and Dragicevic, 2012) or calibration of cellular automata transition rules (Lei et al., 2005).

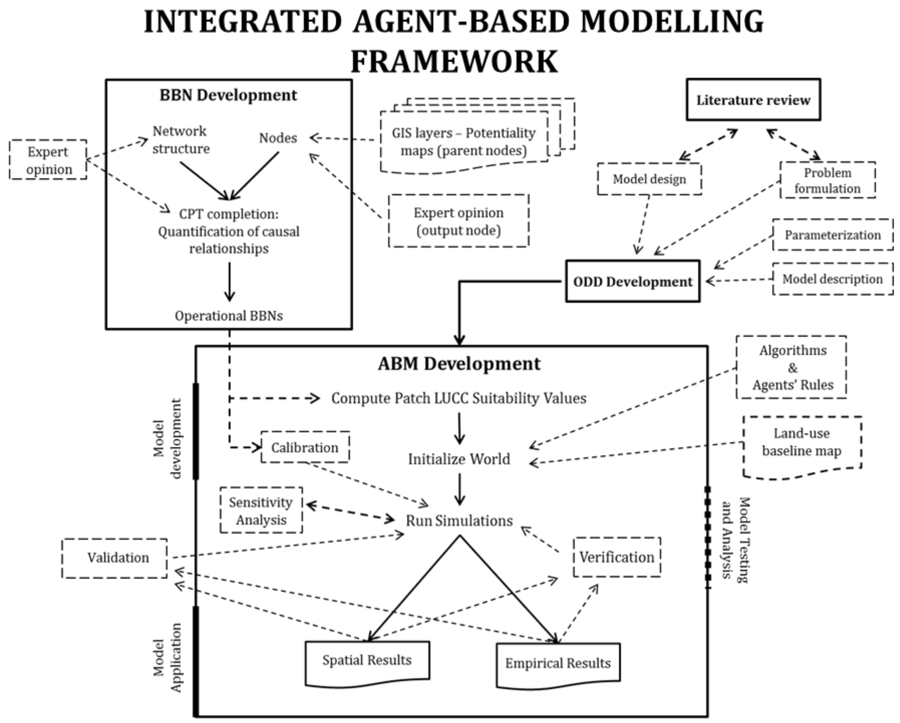


Fig. 2. Model building process for our ABM. Bold arrows indicate the step by step forward direction of the model building process, while bold-lined boxes (e.g. BBN Development) show the main methods and tasks performed. Dashed boxes and dashed arrows refer to the external knowledge, data and processes used within the bold-lined boxes (i.e. main methods and tasks).

2.3 Model overview and data used

2.3.1 Model overview: entities and state variables

The key entities in the model are agents, which represent power governance forces driving LUC (*PG-agents* hereafter); and patches, which represent land-uses (*A* hereafter). *PG-agents* are classified in three types: PG_d-*agents* (governance forces driving development of land for agriculture), PG_p-*agents* (governance forces driving creation of protected areas), and PG_{mr}-*agents* (governance forces driving restoration and maintenance of existing uses of available grassland and forest). Land-uses are classified in three types: A_p (protected areas), A_a (semi-natural areas), and A_d (sugarcane areas). Semi-natural areas are classified in A_{ag} (native pasture) and A_{ap} (production forestry).

The environment consists on a grid of land-uses. *PG-agents* move around the landscape and exert forces on land-uses, thus driving LUC based on probability values obtained from the BBNs (see section below). These BBN values, which change over time based on LUC, state the probability of each land-use to be converted into another land-use, or to remain as the same, and are based on data obtained from GIS layers and expert opinion (see sections below). Furthermore, each land-use computes different sugarcane production, carbon sequestration and biodiversity algorithms every time step, which produce the outcomes described in the 'Results' section.

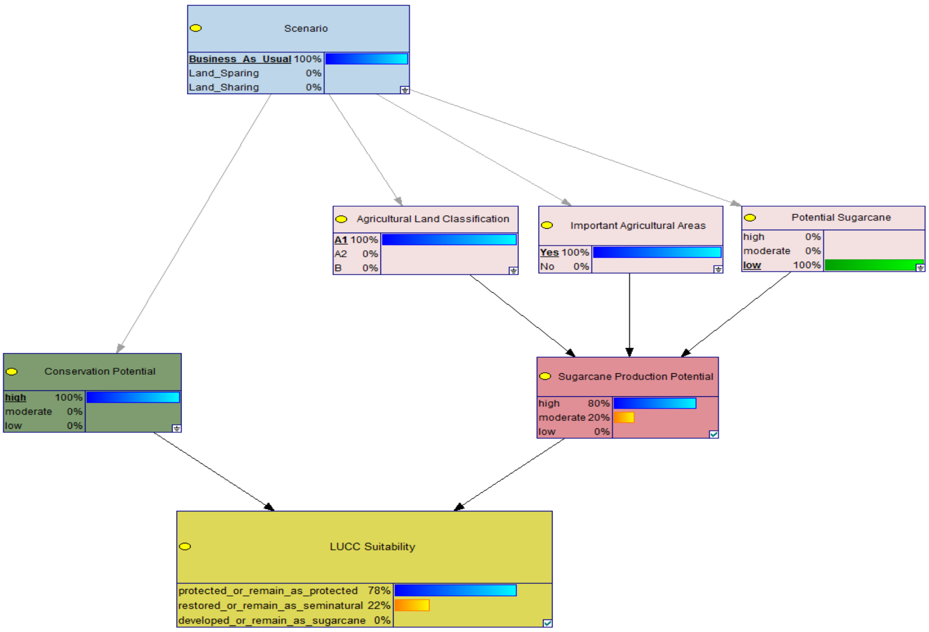
2.3.2 GIS layers and empirical data.

We use the primary land-use and cover map for the Wet Tropics NRM Region (State of Queensland, Department of Agriculture and Fisheries, 2015) as a baseline, which is imported as a vector file into NetLogo. Each patch in our NetLogo model covers an area of 123.64ha of the Wet Tropics NRM Region. Initial biodiversity values are obtained from a biodiversity GIS layer (Mokany et al., 2014), which aligns with the World Heritage criteria. Initial sugarcane yield values are obtained from the Canegrowers Annual Report (Canegrowers, 2005-2016), which considers historical data for the period 2006-2014. Initial sugar monetary value is based on data from the period 2016-2020 (QSL, 2016) and extrapolated to the model simulation period (2016-2030), together with an additional integrated random variability aimed at representing the highly volatile nature of sugar price. Finally, initial carbon sequestration values, both in tonnes and monetary value, were obtained from an above-ground biomass GIS layer (Department of the Environment, Australian Government, 2004) – using the carbon conversion factor recommended by the Intergovernmental Panel for Climate Change for tropical Forests (IPCC, 2006) and the price corresponding to the 2013-2014 financial year (i.e. 24.15 AUD/t), respectively. All the values vary over time based on LUC processes.

Regarding the GIS data driving LUC, available GIS layers from Queensland and Australian Governments are imported as Raster files into NetLogo. These GIS layers provide with values for each land-use, which are then used by the BBNs to state the LUC probability for each land-use; namely Potential Conservation Areas, Above-ground Biomass, Potential Agricultural Areas, Annual Average Rainfall, Potential Plantation Forestry Areas, Potential Grazing Areas, Potential Residential Areas, and Potential Horticulture Areas.

2.3.3 Bayesian Belief Networks.

A BBN is a graphical representation of a set of variables (nodes) and their causal relationships (links) forming a directed acyclic graph (Charniak, 1991). Nodes represent system variables, such as biodiversity or sugarcane yield, while links represent causal probabilistic relationships between two nodes. Within a BBN, each node has a defined set of states/categories along with a Conditional Probability Table (CPT) (see Figure 3 for an example), which defines, for each category, the probability of it occurring given all possible category combinations from the (parent) nodes feeding on this (child) node.



Conservation Potential	high			moderate			low		
Sugarcane Production Potential	high	moderate	low	high	moderate	low	high	moderate	low
protected_or_remain_as_protected	0.7	0.85	1	0.55	0.6	0.65	0.4	0.45	0.5
restored_or_remain_as_seminatural	0.3	0.15	0	0.45	0.4	0.35	0.6	0.55	0.5
developed_or_remain_as_sugarcane	0	0	0	0	0	0	0	0	0

Fig. 3. Example of a Bayesian Belief Network (BBN) developed using GeNIe®, with a Conditional Probability Table (CPT) on the bottom. Both light red and green boxes represent biophysical spatially explicit (i.e. GIS) nodes, while the CPTs from the dark red and yellow nodes are completed using expert knowledge. Coloured bars represent the conditional probabilities for each CPT category. This specific BBN example is computed by semi-natural patches under the BAU scenario. In this particular case, the probability for one semi-natural patch to be protected, having 100% of 'Conservation Potential' and 80% of 'Sugarcane Production Potential', is 78%, being the probability to remain as semi-natural 22%, and to become developed 0%. Due to 78 being higher than 22, the prior LUC would be computed by any PG_{mr}-*agent* moving to this land-use.

One BBN is created for each analysed land-use type (i.e. four in total), thus agents of the same type computing the same BBN. Having three different scenarios (see section below), twelve total BBNs are needed to compute LUC for the entire study area (each BBN has the same structure and nodes as the one shown in Figure 3). The 'LUC Suitability' output node has three different categories, one for each type of LUC (protection, restoration and development). Having a value between 0-1, each category from the output node reveals the probability for each type of LUC to take place in each patch every time step. Each land-use has therefore a probability to change to another land-use type (or to remain as the current land use), based on GIS and expert opinion-based BBNs.

2.3 Scenarios

Table 2 describes each of the three scenarios modelled. LUC target-values are shown as per cent values based on a combination of historical data and expert knowledge.

2030 Scenario	Description
Business As Usual: World Heritage site	Protected areas increase in 10% in order to meet conservation targets as a World Heritage listing site. Production (mainly sugarcane) remains stable over time, due to other regions in Queensland (e.g. Mackay-Whitsundays) being focused on meeting national production demands.
Land Sparing: World Heritage and Queensland's 'food bowl'	The Wet Tropics NRM Region continues to meet conservation targets by increasing protected areas in 5%, yet combined with increases in production of sugarcane by 22%.
Land Sharing: Multifunctional landscapes	Queensland and Australian governments lead a transition towards a more multifunctional governance framework, where wildlife-friendly farming (semi-natural areas) is enhanced (30%) at the expense of sugarcane yields and protected areas.

Table 1. Descriptions and values of the scenarios modelled.

3 Findings

We obtained spatial and graphical results regarding the impact of three different scenarios (BAU, LSH, LSP) on one provisioning ES (sugarcane production), one regulating ES (carbon sequestration) and two biodiversity-related indicators (current biodiversity and extinction debt).

3.1 Estimated spatial impacts

Figure 4 shows the spatially explicit outputs obtained from NetLogo. We produced three output maps for each scenario (i.e. nine maps in total), which represent the spatial distribution of land-uses in three different time steps (years): 2020, 2025 and 2030.

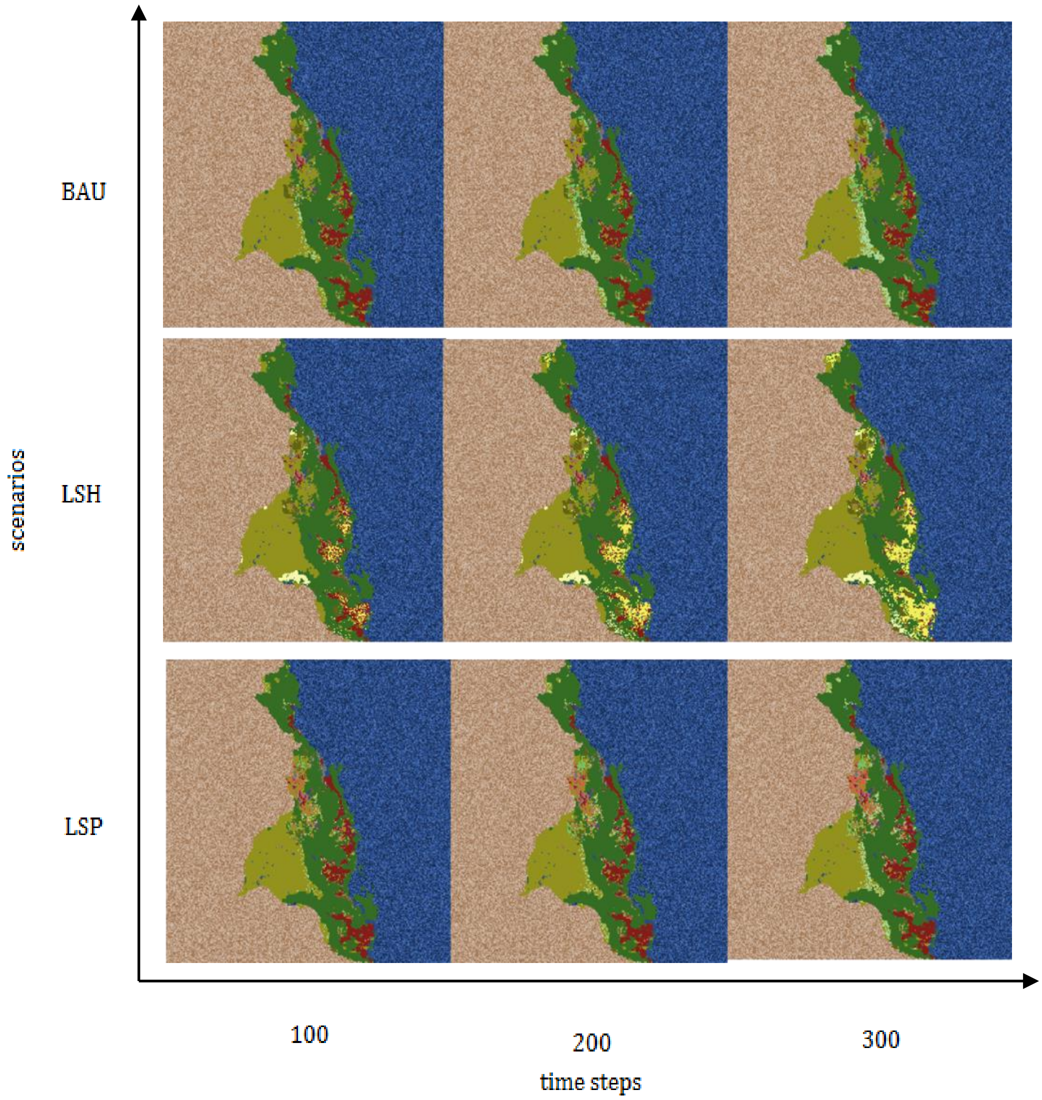


Fig. 4. Scenario outputs for three different time steps: 100 (i.e. 2020 year), 200 (i.e. 2025 year) and 300 (i.e. 2030 year) under each scenario (BAU = top tow; LSH = middle row; LSP = bottom row). Those areas beyond the limits of the case-study area are shown in blue (right) and brown (left), thus representing the Pacific Ocean and other terrestrial ecosystems, respectively. Land-use legend for all the outputs: protected area (green), new protected area (light green), native pasture semi- natural area (dark yellow), production forestry semi-natural area (brown), new production forestry (light yellow), new native pasture (very light yellow/white), sugarcane (red), new sugarcane (light red).

3.2 Estimated empirical/graphical impacts

Figure 5 shows the empirical results regarding the sustainability indicators selected for our case-study. Results .

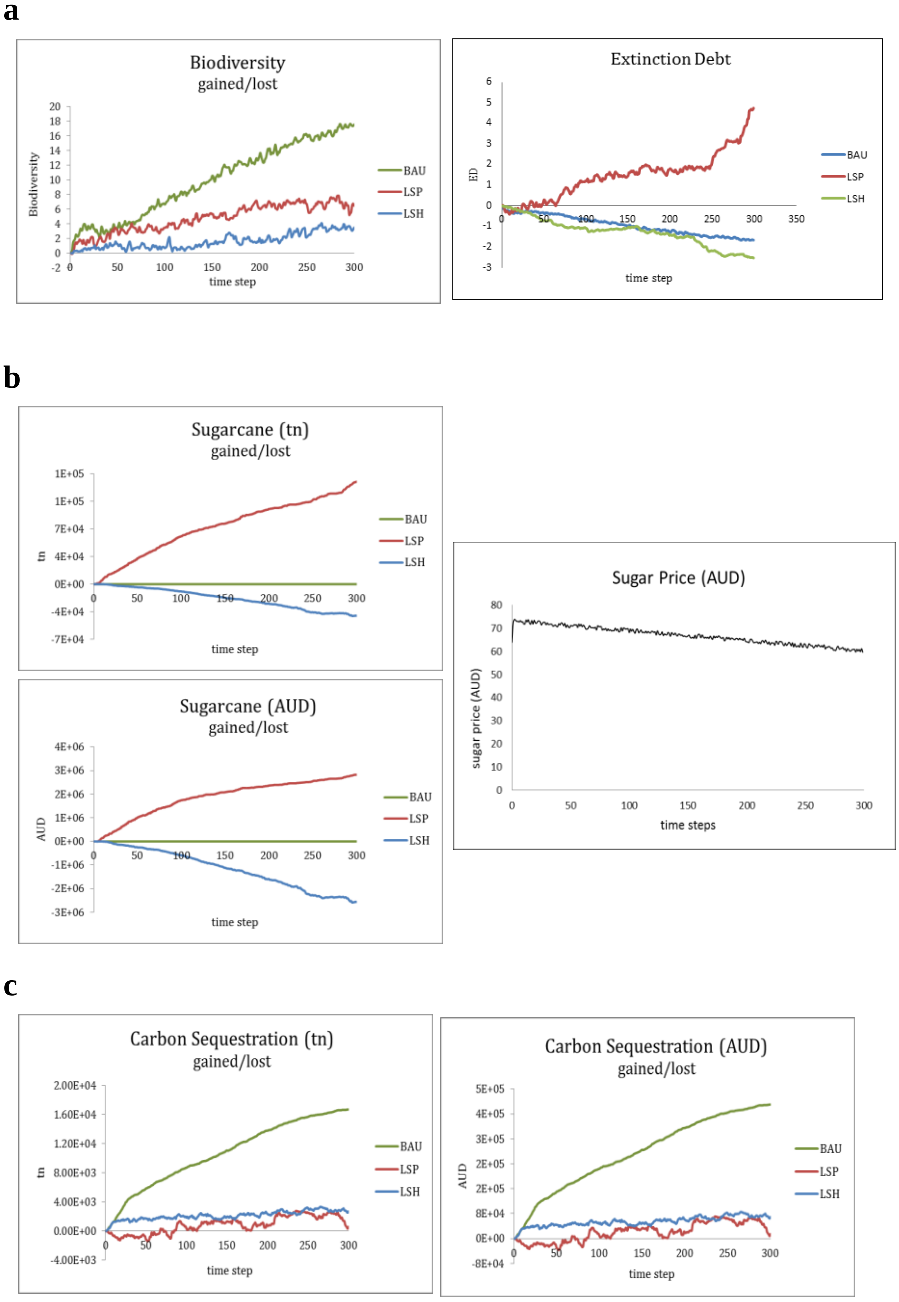


Fig. 5. Graphical empirical scenario results, shown as net gains and losses for each sustainability indicator under each scenario (BAU = green; LSP = red; LSH = blue). Time step 100 refers to the year 2020, 200 to 2025 and 300 to 2030.

Results from Figure 5a represent the total estimated additional biodiversity (left) and extinction debt (right) gained/lost induced by the different scenarios. Biodiversity indicator values (left graph, Figure 5a) in each land-use increase/decrease with the proportion of habitat restored/destroyed in that land-use and its surrounding ones, as well as with patch-connectivity. Extinction debt (Figure 5a, right graph), in ecology, is the future extinction of species due to events in the past, which occurs because of time delays between impacts on species and the species' ultimate disappearance. Both sugarcane and carbon sequestration values (in t and AUD) vary based on LUC

Figure 6 shows the effect of protection and development governance forces in biodiversity in the Wet Tropics NRM Region. Since *PG-agents* conceptually constitute those governance forces and policies driving land protection (PG_p), development (PG_d), and restoration (PG_a), the number of each *PG-agent* type represents the strength/magnitude of the above-noted forces. Therefore, simulations with higher number of initial protection agents (PG_p) than development (PG_d) represent a context where protection forces driving LUC are stronger than development. Based on this, the heatmap on top of Figure 6 shows biodiversity results with one single initial PG_d-*agent* and different initial number of PG_p-*agents* (i.e. weak development forces, varying protection forces), while the bottom heatmap shows results for one single initial PG_p-*agent* and different initial number of PG_p-*agents* (i.e. weak protection forces, varying development forces). Biodiversity variability in the top heatmap is higher than in the bottom heatmap. This shows that biodiversity in the Wet Tropics NRM Region increases considerably with stronger protection forces (top heatmap), while development forces have limited influence on biodiversity (bottom heatmap), even in those scenarios with strong development forces driving land clearing for agriculture (i.e. high number of PG_d-*agent*s, bottom heatmap).

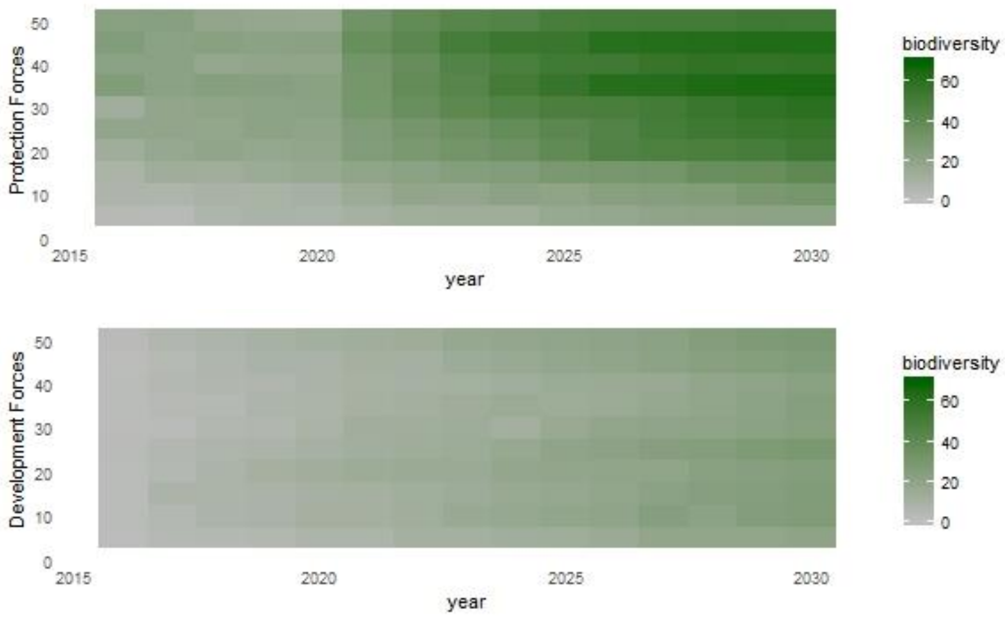


Fig. 6. Impact of protection and development governance and political policy forces on biodiversity.

4 Discussion

4.1 How sustainability was won: integration of bottom-up & top-down forces in the Wet Tropics

Overall model results show BAU as the most suitable landscape management option to enhance landscape sustainability in the Wet Tropics NRM Region. This scenario shows positive trends for both biodiversity-related indicators and carbon sequestration, with steady state sugarcane production. We argue that the strength of the power of governance regimes focused on protecting existing forests, maintaining high biodiversity and limiting land for development in the Wet Tropics NRM Region, is relatively high compared to the strength of the power of governance driving land clearing for agriculture (i.e. development).

Interestingly, protection forces in the Wet Tropics NRM Region did not originate from government's top-down policies, but rather from the growing 'bottom-up' public understanding of the environmental, social and economic significance of wilderness areas in the Wet Tropics (CAFNEC, n.d.). In fact, it was in the 1970s when the lack of substantial environmental movement that had dominated the North Queensland society since settlement in the 1860s started to change. At this point, conservation groups, local citizens, and prominent national and international scientists initiated a battle against the economic forces driving land clearing in the Wet Tropics. This bottom-up 'campaign', which covered a diversity of strategies such as lobbying, direct action, mass mobilisation and political endorsements, culminated in the listing of the Wet Tropics Rainforests on the World Heritage Register in December 1988. Since then, a wide, strong and multilayer conservation policy network managed by Australian and Queensland governments has been created, leading to the current strong institutionalization of biodiversity conservation in the Wet Tropics. As a result of this combination of bottom-up and top-down conservation forces, currently 50% of the Wet Tropics NRM Region is protected, thus enhancing biodiversity and the sustainability of the region.

4.2 Which combination of factors enhance and diminish sustainable development in tropical regions?

The situation in the Wet Tropics NRM Region is atypical compared to other tropical regions, since protection forces continuously limit the potential strengthening of development forces that are enhanced by the current market economy. This contrasts with forces driving protection in most tropical regions not being sufficiently strong to halt land clearing.

Which approach – LSP or LSH – would be more suitable to manage tropical landscapes with a different socio-economic context than the Wet Tropics? Whilst the answer to this question is context-dependent, we argue that LSP is more likely to enhance long-term unsustainability in terms of biodiversity loss and carbon release to the atmosphere in tropical landscapes. This is based on the fact that the stronger market-driven (development) forces compared to protection forces create unbalanced LSP contexts, where land clearing for agriculture is prioritized and enhanced over land protection. The following are some key aspects that could be enhancing development while limiting protection forces in tropical LSP contextsx: (i) funding for development in tropical regions is usually much higher than for conservation (Hill, 2015). For instance, the leaders of the G20 nations gave a huge boost to the power of development regimes by promising to invest 60-70 trillion U.S. dollars on new infrastructure projects by the year 2030 (Hill, 2015). (ii) Profit-seeking businesses are generally given priority over conservation programmes. Brazil stands out in this respect, having one of the fastest increases in agricultural productivity in South America (together with Venezuela, Peru and Colombia) (Ceddia et al., 2014). (iii) The amount of land protected in tropical regions does not normally reach the minimum 17% stated by the Aichi 2020 Targets (e.g. 14.7 per cent in Indonesia, 8 per cent in Malasya, 5.2 per cent in Panama, all in 2014) (World Bank, 2014). (iv) Protected areas are usually located in very remote and isolated areas, thus reducing their positive impact on overall biodiversity (Palomo et al., 2013). (v) Creating new protected areas through biodiversity offsetting should be considered as a valid action only when biodiversity benefits are additional to a baseline scenario, since using unsustainable BAU baseline scenarios will not diminish future threats to biodiversity (Maron et al., 2015). (vi) Public biodiversity discourses, rather than enhancing pro-conservation community sentiments, could be diminishing them (Hill et al., 2015). This idea is based on the concept that protected area creation could lead to a public perception that more and more biodiversity is being protected, which could be resulting in a reduction on the awareness and risks of biodiversity loss, even reaching the policy-making sphere.

Weak environmental governance in tropical countries generally fails at counter-balancing economic powers that continuously seek for short-term profits under the current free-market system. Most tropical regions would therefore need policies and governance frameworks that enhance the conservation sphere of LSP (e.g. through conservation incentives, spatial constraints to agriculture) (CAFNEC, n.d.). Another option to halt biodiversity loss and increase sustainability would be to advocate for LSH approaches, that is, the forces that enhance and maintain traditional, sustainable land-use, alternative sustainable land use, or restore degraded habitat (Hill et al., 2015). Nevertheless, the difficulty for governments to incentivate LSH lies on the fact that this approach usually goes against neoclassical economic theories and macro-economic perspectives driving market economies nowadays (Goulart et al., 2016). Hence, LSH is generally ignored by the current market economy due to its focus on externalities and non-provisioning ES (i.e. cultural, regulating and supporting), which have no direct market value. We argue that, while supporting LSP approaches (and, above all, the development spehere within it) is totally justifiable from a short-term economic perspective, the long-term consequences on both the environment and economy, may be negative.

5 Conclusion

Under the framework considered, and answering our research questions (see [a], [b] and [c] at the end of the Introduction), this paper shows evidence that the current BAU scenario in the Wet Tropics NRM Region is an atypical 'sustainable tropical island' – providing food, conserving biodiversity and sequestering atmospheric carbon – due to the combination of bottom-up and top-down conservation forces. This is an outstanding achievement for a tropical region, considering that the same market profit-seeking forces driving unsustainable land developments in other tropical regions are also present in the Wet Tropics. Due to the fact that protection forces are normally 'weaker' that development in most tropical regions under LSP approaches (see i-vi points in the Discussion section), we argue that the conservation dimenssion within LSP, together with supporitng LSH approaches, should be enhance by governments in tropical regions. Furthermore, we argue that it is not an either-or proposition; both LSP and LSH approaches are not mutually exclusive and we will need a mixture of sharing and sparing to meet conservation goals in a world with a growing demand for different ES. Each geographic context and set of stakeholders will need to explore specific sustainable-smart SES systems based on the particular local and regional socio-cultural, economic and environmental contexts. Thus, the LSP vs. LSH framework has the potential to meet multiple goals that, when integrated within spatially explicit models, may provide sustainable solutions within complex social-ecological systems.

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