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PERSPECTIVE

PEOPLE AND NATURE BRITISH ECOLOGICAL SOCIETY

# Red and green loops help uncover missing feedbacks in a coral reef social–ecological system

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## Abstract

1. Social–ecological systems (SES) exhibit complex cause-and-effect relationships. Capturing, interpreting, and responding to signals that indicate changes in ecosystems is key for sustainable management in SES. Breaks in this signal–response chain, when feedbacks are missing, will allow change to continue until a point when abrupt ecological surprises may occur.
2. In these situations, societies and local ecosystems can often become uncoupled. In this paper, we demonstrate how the red loop–green loop (RL–GL) concept can be used to uncover missing feedbacks and to better understand past social–ecological dynamics. Reinstating these feedbacks in order to recouple the SES may ultimately create more sustainable systems on local scales.
3. The RL–GL concept can uncover missing feedbacks through the characterization of SES dynamics along a spectrum of human resource dependence. Drawing on diverse qualitative and quantitative data sources, we classify SES dynamics throughout the history of Jamaican coral reefs along the RL–GL spectrum. We uncover missing feedbacks in red-loop and red-trap scenarios from around the year 600 until now. The Jamaican coral reef SES dynamics have moved between all four dynamic states described in the RL–GL concept: green loop, green trap, red loop and red trap.
4. We then propose mechanisms to guide the current unsustainable red traps back to more sustainable green loops, involving mechanisms of seafood trade and ecological monitoring. By gradually moving away from seafood exports, Jamaica may be able to return to green-loop dynamics between the local society and their locally sourced seafood. We discuss the potential benefits and drawbacks of this proposed intervention and give indications of why an export ban may insure against future missing feedbacks and could prolong the sustainability of the Jamaican coral reef ecosystem.
5. Our approach demonstrates how the RL–GL approach can uncover missing feedbacks in a coral reef SES, a way the concept has not been used before.

We advocate for how the RL–GL concept in a feedback setting can be used to synthesize various types of data and to gain an understanding of past, present and future sustainability that can be applied in diverse social–ecological settings.

KEYWORDS
coral reef management, historical, interventions, Jamaica, leverage points, mixed methods, regime shift, sustainability

## 1 | INTRODUCTION

Increased globalization has been one of the underlying factors driving observed increases in human development (e.g. Human Development Index; Cumming & von Cramon-Taubadel, 2018; United Nations Development Program, 2018). However, the increased connectivity of economies, ecosystems and human societies on a global level has been argued to be detrimental to the sustainability of local social–ecological systems (SES) when feedback relationships that indicate overharvesting of natural resources or environmental impacts are weakened or lost (Berkes, 2007; Levin, 1999; Nyström et al., 2019). This weakening—or decoupling—can emerge as the geographical distance between the location of consumption and production increases (Anderson, 2010; Clapp, 2014; Nyström et al., 2019). Overfishing of local fish stocks, for example, can be masked by importing fish caught elsewhere, leaving consumers relatively unaffected and unaware of ongoing changes in the ecosystem (Crona et al., 2016). For instance, the United Kingdom (UK) increased their imports of Atlantic cod from Iceland and the Faeroe Islands between the late 1980s and 1990s (Crona et al., 2016). Because cod was available in UK markets from multiple competing sources, the prices did not represent the decreasing cod stocks in local UK waters. This masked the mechanism for UK consumers to keep track of the increasing cod rarity and hence did not cause consumers to match their consumption patterns to the state of local ecosystem degradation. Such mechanisms are often referred to as 'feedback mechanisms' because they have the potential to feed information about the state of a system back to society.

Capturing, interpreting and responding to signals that indicate changes in ecosystems are key facets of sustainable management in SES. If feedbacks are ignored or masked (e.g. by trade), change is allowed to pass unnoticed until a point when an abrupt ecological surprise (i.e. regime shift) may occur. Once manifested, the new ecological state can be difficult, very costly and potentially even impossible to reverse (Nyström et al., 2012). Pathways toward improved local sustainability have to feature managing feedbacks that underpin social–ecological trajectories.

Here, we demonstrate how the RL–GL concept highlights missing feedbacks and how it can be used to synthesize various types of data and to understand past, present and future sustainability in diverse social–ecological settings. Our study is the first that is integrating these two approaches to unpack social–ecological dynamics for improved sustainability of SES.

### 1.1 | Reinstating missing feedbacks to recouple social–ecological systems

When feedbacks are masked, they are referred to as 'missing feedbacks' (Barnett & Anderies, 2014; Crona et al., 2016). In the context of social–ecological dynamics, this often means that the social system gets decoupled from the local ecosystem (Hoole & Berkes, 2010), which opens unsustainable pathways that the SES may follow (Crona et al., 2016). To avoid this from happening it is critical to reinstate missing feedbacks and recouple the SES by 'closing the loop' between humans and ecosystems (Patterson & Coelho, 2008). A global example of this recoupling feedback approach is the current climate change discussion. Carbon taxes or carbon credits are meant to act as a 'global' feedback to recouple anthropogenic changes to the atmospheric system back to society (Van der Ploeg, 2014). Cod prices in the UK provide a local example; the missing feedbacks mentioned above could be reinstated by strengthening information flow from fishers to consumers or by directly increasing overfishing awareness in citizens and political actors through publicity (Crona et al., 2016). Another example of reinstating feedbacks comes from the Etosha National park in Namibia (Hoole & Berkes, 2010). Decoupling was connected to the loss of Herero knowledge of the park, which led to failing wildlife conservation initiatives and exacerbated poverty levels in local Herero communities. Reinstating this missing feedback, through management collaboration between the park and Herero communities, as well as Herero inclusion in park management and as employees was used to reinstate feedbacks, ultimately improving the outcomes for the Herero and conservation management. Addressing missing feedbacks can have a transformational impact on the SES but it requires very detailed knowledge of the SES dynamics to uncover where feedbacks are missing (Crona et al., 2016; Meyfroidt & Lambin, 2009; Patterson & Coelho, 2008). Individual case studies are extremely variant in their display of feedback dynamics and detecting missing feedbacks will vary from case to case.

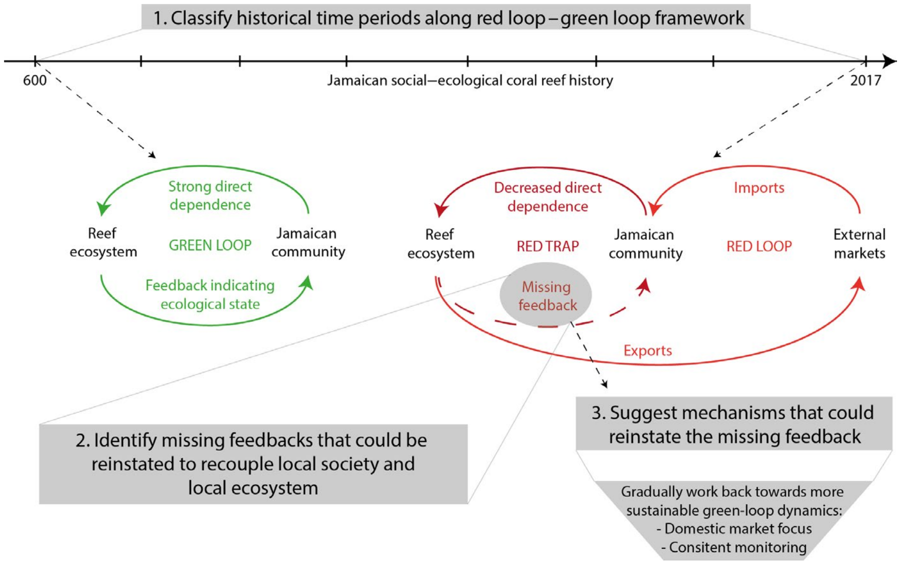

**FIGURE 1** Summary schematic of our approach to (1) using red-loop green-loop classification of historical time periods to (2) uncovering missing feedbacks for which we suggest (3) mechanisms to reinstate the feedbacks and recouple the coral reef social–ecological system

## 1.2 | Using the 'red loop–green loop' model to identify missing feedbacks

We argue that a framing is required which assists with feedback classification and can identify missing feedback scenarios. The 'red loop–green loop' (RL–GL) concept (Cumming et al., 2014) provides this framing for two differing forms of ecosystem dependence and sustainable resource use.

The RL–GL concept proposes that human resource dependence on a national scale tends to follow one of two fundamentally different trajectories that are reinforced by weak ties with local ecosystems and strong ties with distal systems (red loop), or strong ties with local ecosystems and weak ties with distal systems (green loop; Cumming & von Cramon-Taubadel, 2018). In both red- and green-loop countries, the entire economy or certain economic sectors can evolve into trap situations that can severely threaten the long-term sustainability of the current trajectory (Cumming et al., 2014). Green traps can occur as the human population in a green-loop economy grows without adequate food production from the local ecosystem, leading to a spiral of increased overharvesting and environmental degradation (Steneck, 2009). To avoid this green-trap situation, societies can divert their dependence towards external ecosystem services, for instance by means of food import, which would lead towards red-loop dynamics. In a red-loop trajectory, the economy's ecological impact reaches to distal ecosystems as well as the local system. For instance, reforestation in parts of Vietnam between 1987 and 2006 was achieved at the expense of forest displacement from other parts of the country as well as partly illegal imports from deforestation in neighbouring countries such as Cambodia and Laos (Meyfroidt & Lambin, 2009). The example illustrates a red-trap situation where supply and consumption are maintained without recognition of the ecological degradation entails in other local ecosystems due to missing feedbacks.

In summary, as sectors in the economy relying on local ecosystems for resources approach a red trap and the economy as a whole increases its dependence on distal systems, the likelihood of missing feedbacks between the country's society and local ecosystems increases. Therefore, societal and ecological dimensions of the SES run the risk of decoupling and a recoupling of the SES becomes more necessary for local system sustainability.

We argue that once the missing feedbacks have been identified, interventions to reinstate them could recouple local SES and move economic sectors out of red- or green-trap trajectories. Applying the RL–GL concept to historical SES data can facilitate an understanding of how feedback dynamics have changed through time (Cumming et al., 2014; Hamann, Biggs, & Reyers, 2015) and what trajectory an economic sector is currently following (Cumming & von Cramon-Taubadel, 2018). This can highlight points where the SES decoupled and thus identify opportunities to recouple the SES and avoid trap scenarios.

In this study, we apply the RL–GL framework to understand and classify the SES dynamics in the context of Jamaican coral reefs (Figure 1), using mixed historical data dating back to roughly the year 600. With this historical understanding, we focus on uncovering missing feedbacks between the Jamaican people and their coral reef system. Lastly, we propose mechanisms that could move the current Jamaican coral reef SES out of recently assumed red-trap dynamics.

## 2 | JAMAICAN CORAL REEF SES DYNAMICS THROUGH TIME

We identified and categorized social–ecological trajectories and feedbacks of Jamaican coral reefs across eight time periods (Table 1), from around 600 to the present. For the first six time periods (Ostionan, Meilican, Spanish occupation, British colonization, Post-emancipation and World Wars I & II), the available data are mostly qualitative. Hardt (2009) and Hicks, Crowder, Graham, Kittinger, and Cornu (2016) conclusively reconstructed the social–ecological dynamics for these time periods and we use them as our primary reference to infer about the nature (red or green loop) of those dynamics.

**TABLE 1** Historical data types and sources per time period of Jamaican history

| Time period | Data type | References |
|---|---|---|
| Ostionan (600–900)<br>Meilican (900–1500) | Qualitative:<br>Kitchen midden analyses | Hardt (2009) and Hicks et al. (2016) |
| Spanish occupation (1509–1655)<br>British colonization (1656–1834)<br>Post-emancipation (1834–1900)<br>World Wars I & II (1901–1945) | Qualitative:<br>Sailors' logbooks & historical descriptions by naturalists, historians & fisheries scientists | Beckwith (1929), Hardt (2009), Hicks et al. (2016), Munro et al. (1971) and Thompson (1945) |
| Post-war (1946–1985)<br>Shifted reefs (1985–2017) | Quantitative:<br>Fisheries, demographic, economic and ecological data | Clayton (2001), FAOSTAT (2019), Hardt (2009), Hicks et al. (2016), Hughes (1994), Lingard et al. (2012), Oswald (1963), United Nations Development Program (2018) and World Bank (2019) |

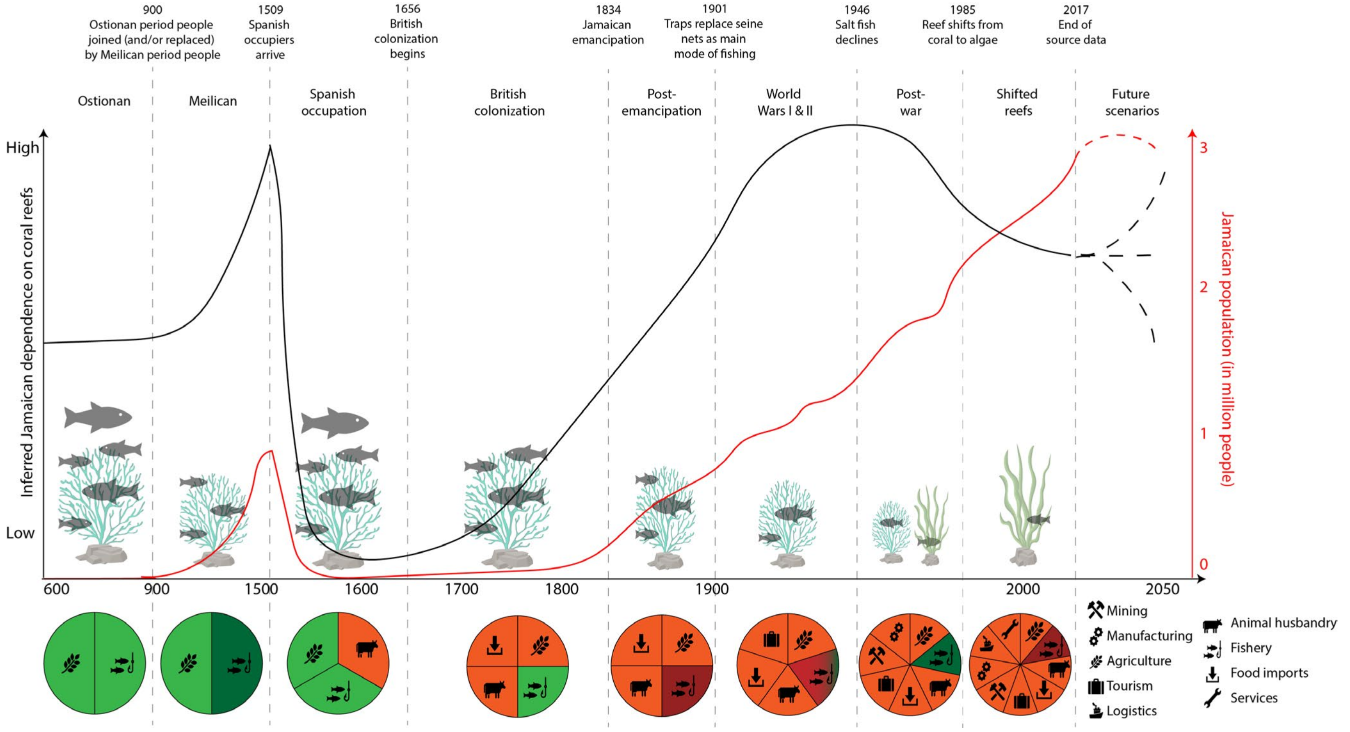

**FIGURE 2** Jamaica's inferred dependence on coral reefs from low to high (black line) and human population (red line) through time. Time up to future scenarios is split into eight separate time periods and for each we determined ecological reef regime state of the reef (fish & coral/algae symbols) as well as major economic state of Jamaica (pie graphs). Colour of the pie graph segments indicates Jamaica's economic state along the RL–GL spectrum: green loop (light green), green trap (dark green), red loop (light red), red trap (dark red); population based on Hardt (2009; up to 1950) & United Nations, DESA, Population Division, World Population Prospects 2019, http://population.un.org/wpp/ (from 1950)

Most quantitative data became available from 1950 and we use them to infer about social–ecological dynamics in the last two time periods (Post-war and Shifted reefs; Clayton, 2001; FAOSTAT, 2019; Hardt, 2009; Hicks et al., 2016; Hughes, 1994; Lingard et al., 2012; Oswald, 1963).

To illustrate social–ecological dynamics between the Jamaican society and their coral reefs over eight time periods, we used a mixed quantitative and qualitative approach. For each time period, we inferred Jamaican social–ecological dynamics from indicators of social change, changes in human population size, economic diversification, as well as ecological change (Figure 2). We then focused on the social–ecological dynamics around local Jamaican coral reefs, viewed them as an individual economic sector, as well as through an RL–GL lens for each of the time periods and suggest mechanisms to approach green-loop dynamics in future scenarios (Figure 3).

## 2.1 | Ostionan period (600s–900s): Green-loop dynamics

From roughly the 600s–900s, Jamaica was inhabited by Ostionan period people and dependence on coral reefs was largely based on fishing (Figure 2). This resource extraction increased with a growing

**FIGURE 3** Schematic showing social–ecological dynamics focussed on the dependence of the Jamaican community on their coral reefs and categorization of these dynamics along the spectrum of the RL–GL model leading to a concept of future dynamics where we suggest a conceptual system with mechanisms to reinstate the missing feedbacks and to recouple the social–ecological system

human population with no indication of trade or other connections to other systems (Hardt, 2009), as well as a relatively small population size, leading to the classification of this period as a green-loop state (Figure 3).

## 2.2 | Meilican period (900s–1500s): Green-trap dynamics

During the Meilican period, the human population on Jamaica grew rapidly and by 1500 had reached ~1 million people (Hardt, 2009; Hicks et al., 2016; Figure 2). Decreasing reef fish catch sizes indicate that the reef ecosystem was overexploited under the pressure of the growing human population and there is no evidence of trade prior to the first European contact that could have reduced pressure on the coral reef ecosystem (Hardt, 2009). Based on gradually decreasing fish sizes in kitchen middens suggesting a 'fishing down the food web' situation (Pauly & Palomares, 2005), we concluded that the SES between the Jamaican people and the reef ecosystem during the Meilican period was characterized by green-trap dynamics (Figure 3).

## 2.3 | Spanish occupation period (1509–1655): Green-loop dynamics

With the Spanish occupation in 1509 the Jamaican population declined significantly due to the introduction of new diseases and harsh treatment of the local population (Hicks et al., 2016). By the mid-1510s, the population had been reduced by over 99% from the Meilican period, to approximately 5,000 people, which lessened pressure on the reef ecosystem (Hardt, 2009; Figure 2). Pressure was further reduced via an alternate source of protein by the introduction of pigs and cattle from Spain (characteristic of a red-loop dynamic), resulting in a temporary recovery of reefs (Hardt, 2009). Due to these two pressure reduction factors and minimal dependence on coral reef resources, the local SES returned to a green loop during Spanish occupation (Figure 3).

## 2.4 | British colonization period (1656–1834): Green-loop dynamics

With the colonization by the British in 1656, Jamaica was being developed into a hub for international trade. Sugar, coffee and bananas were increasingly used as trade commodities for salt fish from the UK, USA and Canada (red-loop dynamic; Figure 2). As a result of this resource diversification, reefs were further relieved from fishing pressure (Hardt, 2009; Hicks et al., 2016). The human population of Jamaica started to grow rapidly with the increase in slavery (>300,000 slaves by 1810) as the colonizers expanded their plantations (Hicks et al., 2016). Again, the reef system began to show signs of overexploitation around 1800 as reef fish were increasingly used as food for the plantation owners (Hardt, 2009). During British colonization, the Jamaican community gradually came to re-kindle their dependence on the reef system after barely depending on it during Spanish occupation. Although reef dependence was largely based on subsistence fishing, fishing regulations (e.g. minimum mesh size for fishing nets) put in place by the colonizers suggest that there was an awareness of changes occurring in the local SES and a feedback between society and the reef ecosystem existed (Hardt, 2009). While the larger part of the Jamaican economy was involved in global trade and hence red-loop dynamics (Figure 2), the coral reef SES dynamics remained localized and in a green loop (Figure 3).

## 2.5 | Post-emancipation period (1834–1900): Red-trap dynamics

With emancipation in 1834, Jamaica's human population surged towards Meilican levels (~1 million by 1900) and reef dependence shifted from feeding the local population to using reef fish as a trading commodity for salt fish (Figure 2), which the Jamaican community had become used to during times of slavery (Hicks et al., 2016). The salt fish dependence was so strong that by the 1830s, local reef resources (including fish and coral) were traded to be able to import salt fish from the USA, Canada and the UK (Hardt, 2009). This indirect dependence on local reefs for trade masked the feedback within the SES and began to decouple the reef environment from the local society, likely for the first time in Jamaican history. The increased fishing of reef fish for trade with salt fish producing countries, shifted the coral reef SES dynamics from green loop to red trap (Figure 3).

## 2.6 | World Wars I & II period (1901–1945): From red- to green-trap dynamics

With the advent of tourism and urbanization in the 1900s, red-trap dynamics were further reinforced (Beckwith, 1929; Hicks et al., 2016; Thompson, 1945; Figure 2). Accelerated population growth in the early 1900s led Jamaicans to depend on reef resources for both subsistence and trade (Hardt, 2009). Technological development of fishing gear, especially the adoption of wire mesh fish traps in the 1910s (Munro, Reeson, & Gaut, 1971), caused a shift in dominant fishing mode from seine nets to traps (a technique with even heavier impact on purely reef-dwelling fish) and spiralled further reef degradation (Hicks et al., 2016).

With the onset of World War II, trade suffered a dramatic decline and the Jamaican population had to increasingly rely on local reef fish for food instead of imported salt fish. Green-loop dynamics were forced to be resumed between Jamaican society and reef ecosystem and the SES began to recouple. In 1945, Jamaica's dependence on local fish stocks peaked (Hardt, 2009) and overfishing of near-shore fish stocks was officially recognized for the first time by government fisheries scientist E. Thompson (1945). Due to a rapidly growing population (~1.3 million in 1945), limited economic diversification and Jamaican reef dependence rising as a result, the human population quickly outgrew the provisioning capacities of the reef ecosystem (Hardt, 2009). We argue that the SES could not sustain this quick fall-back on the reef ecosystem for resources during WWII and the resumed green-loop dynamics quickly manifested as green-trap dynamics (Figure 3).

## 2.7 | Post-war period (1946–1985): Green-trap dynamics

As Jamaica's dependence on local reefs for food peaked, the government established the Fisheries Division and developed an off-shore fishery (Oswald, 1963) to be able to keep up with the increasing demand for seafood (Figure 2). Thompson's suggestions to subsidize job transitions for fishers into other jobs were ignored, and the expansion of the reef fishery was instead heavily subsidized in the 1970s and 1980s (Hardt, 2009), which reinforced the green-trap dynamics. In parallel, increasing urbanization, tourism and industrialization (e.g. development of large-scale bauxite mining) were causing reef degradation through pollution of near-shore waters (Hardt, 2009; Hicks et al., 2016). During the 1980s, Jamaica also reported the highest regional deforestation rates, leading to a substantial loss of mangroves (Agard et al., 2007). In 1983–1984, reefs suffered surges of hurricane damage and a sea urchin disease, which in combination with overfishing led to an ecological regime shift where coral reefs became rapidly overgrown by algae (Hughes, 1994). This regime shift and the noticeable catch reductions of reef-dwelling and reef-associated fish species due to overfishing (Figure S1) caused a further spatial expansion of Jamaica's fisheries so that the most productive fisheries were now in far off-shore environments (Lingard et al., 2012; Oswald, 1963). The combined effects of reduced catches from reef fisheries and resulting further fisheries off-shore expansion, as well as the coral reef regime shift, led Jamaican social–ecological reef dynamics to spiral into a green trap (Figure 3). By the late 1980s, Jamaica's economy had diversified and moved into globally connected red-loop dynamics (e.g. revamping salt fish trade), which in part compensated for the heavily degraded reef ecosystem (Figure 2).

## 2.8 | Shifted reefs period (1985–2017): Red-trap dynamics

Following the ecological regime shift, the reef system was severely degraded and the dependence of Jamaicans on the reefs was decreasing. The percentage of employed fishers in the rising Jamaican population declined (FAOSTAT, 2019) and workers in non-ecosystem service sectors increased (Clayton, 2001; Figure 2). Jamaica's fisheries catches were largely made up of subsistence catches, but a part was, once again, used for exports (Figure S1; FAOSTAT, 2019; Lingard et al., 2012). Resuming the resource extraction from the exhausted reef ecosystem for trade, again led to the missing feedback and repeated the decoupling of the SES we described for the post-emancipation period and dynamics of a red trap (Figure 3).

## 2.9 | Jamaica's recent red-loop economy supporting a red-trap coral reef SES

Although the Jamaican coral reef SES was kept in a red-trap situation between 1990 and 2017, the country increased its Human Development Index (HDI) from 0.638 to 0.732 (14.8% increase; United Nations Development Program, 2018). Generally, red-loop and green-loop countries appear to separate along a gradient of the HDI, where HDI class 1 countries assume red loops and HDI class 4 countries assume green loops, while HDI class 2 and HDI class 3 countries are more difficult to classify and show characteristics of both loops (Cumming & von Cramon-Taubadel, 2018). Economic diversification allowed Jamaica with its ~2.9 million population (Figure 2), to be placed in a HDI class 1 in 2017 (United Nations Development Program, 2018), at the median of red-loop countries (HDI of ~0.7; Cumming & von Cramon-Taubadel, 2018). The economic stability gained from diversification has allowed some other nations to improve local ecosystem sustainability (Hansen et al., 2018; Martens & Raza, 2010). A diversified economy is a relatively recent development for Jamaica that had not yet developed when the local SES attempted to move away from red-trap dynamics (i.e. during the World Wars I & II period, Figure 3). A diverse, largely red-loop economy that can lessen the requirements placed on the local coral reef SES could be of great assistance in intervening with current local reef SES red-trap dynamics, provided that the correct guidance is applied to proposed interventions. We propose a set of mechanisms for current Jamaican red-trap dynamics that are meant to reinstate a feedback between society and reef ecosystem to recouple both.

# 3 | REINSTATING MISSING FEEDBACKS IN A LOCAL RED-TRAP SYSTEM

Based on the historical assessment of Jamaican SES dynamics, we discuss possible interventions that may lead to a recoupled Jamaican local reef SES. Highlighting missing feedbacks can help steer a system out of red-trap dynamics (Figure 3). Importantly, we propose a set of mechanisms that are supposed to tackle the systemic design of the Jamaican coral reef SES rather than only few systemic parameters. This prioritization of interventions is highlighted by the 'Leverage Points' perspective (Abson et al., 2017; Fischer & Riechers, 2019; Meadows, 1999) and guided our proposed intervention. The leverage points perspective argues for prioritization of interventions that have large transformational potential (deep leverage) over those that are usually used but have little to no impact (shallow leverage; Abson et al., 2017). These deep leverage points are difficult to implement because they often prioritize tackling system design and intent (deep leverage) over system parameters (shallow leverage), which is why they are under-used and under-researched (Fischer & Riechers, 2019). Their transformational potential applies well to our case study and hence guides the interventions we are proposing to implement here.

### 3.1 | Pursuing a green-loop coral reef social–ecological system design through seafood export bans

With an annual per capita fish consumption of 25.8 kg (2017), Jamaica ranks amongst the highest seafood consuming countries in the Americas. Yet, 79% of Jamaica's supply of all fishery products consumed domestically in 2017 stemmed from imports (FAOSTAT, 2019). Our historical analysis of Jamaica shows that seafood exports were a main driver in decoupling the feedback within the coral reef SES, especially in the post-emancipation period, World Wars I & II period and the shifted reef period (Figure 3).

We propose an intervention strategy following a deep leverage point in the system's design (Abson et al., 2017). The local coral reef SES could be gradually designed towards green-loop dynamics in which locally sourced reef produce are rerouted from exports to domestic markets. In envisaging the local reef SES, local seafood catches from the near-shore and off-shore environment would not serve as exports and only be used for domestic markets, including consumption (e.g. by locals) and sales (e.g. to tourists). A system averse to exports of locally sourced seafood would reinstate a direct feedback between the Jamaican society and the local reef ecosystem. However, for this reinstated feedback to be sustainable, and avoid a green-trap scenario, careful monitoring and management of the resource will be necessary. This could lead to the desired recoupling of the Jamaican coral reef SES and enable movement towards locally connected green-loop dynamics within an otherwise globally connected red-loop system.

A coral reef SES in which seafood is locally sourced and used, would, according to RL–GL thinking, be more sustainable than the current red-trap situation (Cumming et al., 2014). For this reinstated feedback to have the desired effect, it is crucial that the information on the ecosystem's state that is fed back to the Jamaican society is reacted on appropriately. This means that the feedback is not ignored, as was the case in 1945 when the suggestions and warnings by fisheries scientist Thompson were ignored by the Jamaican government (Hardt, 2009). Existing feedbacks that are ignored can also have destructive effects on the ecosystem (Degnbol & McCay, 2007), although, our historical analysis of the Jamaica case indicates that missing feedbacks were more frequently occurring in the coral reef SES than ignored ones.

### 3.2 | Strengthening green loops in other regions

Examples of mechanisms that can assist the transition from red-trap to green-loop dynamics exist in the literature. As in the cod example above, one mechanism to reinstate the missing feedbacks could be in strengthening information flow from fishers to consumers (Crona et al., 2016). Eco-labels could provide this transparency to consumers; specifically, labels with a 'locally grown' claim have been suggested to be more highly valued by consumers in the United States (Giovannucci, Barham, & Pirog, 2010; Loureiro & Hine, 2002; Onozaka & McFadden, 2011). A 'locally sourced' eco-label could lend itself to reinstate sustainable stewardship of local reef produce. Besides such labelling schemes, education and public campaigns are central instruments for consumers to make informed decisions that can help reinstate feedbacks (Crona et al., 2016). Moreover, traceability is a key mechanism in this context to ensure supply chains are devoid of unacceptable behaviour, ranging from illegal sourcing and forced labour to poor sanitation and mislabelling (Nyström et al., 2019).

Addressing unsustainable trajectories from deep within a SES is complex and sometimes difficult to monitor through time. For example, it has been suggested that many South-East Asian economies (van Mulekom et al., 2006) could alleviate malnutrition and poverty by redirecting the considerable resources gained through fishing away from exports and towards domestic use, particularly given the rich micronutrient yields in these catches (Hicks et al., 2019). For a region as large as South-East Asia, it is difficult to understand whether these suggestions have led to improvement, largely because the documentation is very inconsistent (Béné et al., 2016). However, shifts towards fishing for domestic markets have been noted in the province of Phang-nga, Thailand (Jones, Gray, & Umponstira, 2010) and the Philippines (Fabinyi, 2016). Some South-East Asian countries might not be as economically well-placed to manifest a green-loop dynamic for their local reef ecosystems, since the marine seafood sector creates a large percentage of national revenue. For instance, Indonesia appears to favour an increase in marine seafood exports, believing that further development of marine resource exports (4.2 billion USD; FAOSTAT, 2018) is vital for bringing Indonesia out of its recent economic crisis (Rizal, Herawati, Zidni, Apriliani, & Ismail, 2018).

A recent study from Seychelles demonstrated substantial catch declines in prized red snapper species, locally called 'bourzwa' (Robinson et al., 2020), with exports leading to price increases to the point where the fish became unaffordable to locals. In attempts to protect livelihoods, lower the prices and achieve recovery of the species' stocks, export bans from 2020 have been proposed for bourzwa (Robinson & Graham, 2020). Similar price dynamics might be driving the Jamaican affinity for imported fish consumption in our case study. Export bans could lead to price reduction in local reef fish, make it more affordable for locals and hence increase their consumption. In the optimal case, this could gradually increase local seafood sustainability, as well as increase the perceived value of the local reef ecosystem and an increased sense of stewardship (Chapin et al., 2010) to gradually close the feedback loop.

The success of an export ban, however, depends on the availability of data to fully understand SES dynamics. In the Seychelles example, Robinson et al. (2020) use detailed fisheries data to show that local markets were already buying four times as much bourzwa as is exported and elude to the limited likelihood that export bans may have on reducing bourzwa prices, and that other local fisheries management efforts will be key to sustainability (Robinson et al., 2020). Comparative data in Jamaica are very limited, with the most recent (2002) specific seafood export information noting lobster, conch and 'some fish' (FAOSTAT, 2019). An export ban, if implemented, should be preceded and accompanied by detailed monitoring of fisheries data to uncover if similar dynamics to Seychelles could be at play in Jamaica. Similarly, an example from Palau, where the government banned 80% of fishing from foreign vessels in their off-shore waters caused effort to transition to near-shore waters, increasing the pressure on reef fish species (Dacks, Lewis, James, Marino, & Oleson, 2020).

The above examples demonstrate the possible effectiveness of an export ban for recoupling feedbacks within an SES. Yet, these case studies also emphasize the importance of having detailed data to understand past, current and future SES dynamics. In the following section, we propose where further data could enhance the establishment of a green-loop coral reef SES.

### 3.3 | Monitoring required for the green loop

Based on our historical analysis of SES dynamics, we argue that the diverse red-loop economy of Jamaica is at a point where the small export revenue derived from the local reef fishery (12.9 million USD) could be rerouted to domestic markets to increase local coral reef SES sustainability (FAOSTAT, 2019). In our historical analysis, when Jamaica was forced to resume green-loop dynamics for the local reef SES during WWII, the economy had only five main sectors whereas today it has nine (World Bank, 2019). Jamaica acts as a conceptual example in which we demonstrate how a diverse economy could help leverage a green-loop pathway for its local ecosystem dependence.

For a green loop through export bans to work, a thorough, species-specific comparison of seafood imports and exports needs to be established to be able to gauge the full benefit of an export ban (Robinson & Graham, 2020). In addition, the local and international demand for species-specific seafood needs to be thoroughly understood so that the government can anticipate potential knock-on effects (Dacks et al., 2020).

Consistent ecological monitoring of the Jamaican reef system has usually been scarce, as we have seen through our historical analysis. The peak of ecological monitoring was likely during the benthic regime shift and even recently, consistent government-led ecological monitoring of the reefs has been spatially and temporally fragmented (Creary, Smith, & Green, 2012; Lapointe, Thacker, Hanson, & Getten, 2011). Consistent monitoring should provide concurrent ecological awareness that would enable more reactive management to ecological change in the future.

The interventions we suggest above were formulated by searching for points in the system's design that we could leverage to prolong its sustainability. We decided to pursue the design of a green loop coral reef SES and we highlight the benefits and drawbacks for this pathway, but our suggestions are not exhaustive. For instance, within the leverage points framework, there are more pathways which could lead to different interventions (e.g. pursuing the alteration of the system's intent through alternative governance) which future studies could explore.

## 4 | CONCLUSION

Within sustainability research there are different concepts to disentangle social–ecological dynamics. We demonstrate the value of examining complex dynamics through a conceptual lens by using Jamaica's complex coral reef SES dynamics as a case study. We identified a decoupling in the SES using the feedbacks concept—the feedbacks from coral reefs to Jamaican society had become masked. The resulting missing feedbacks were uncovered with the RL–GL concept. Throughout Jamaica's social–ecological history, the SES dynamics between people and the coral reef ecosystem have moved between all four dynamic states described in the RL–GL concept: green loop, green trap, red loop and red trap.

Jamaica's society has experienced the effects of a degrading near-shore system in the past, at the very least in the form of changes in the types of seafood available for consumption. In its current form, the Jamaican economy has effectively diluted any severe repercussions through a rapidly diversifying economy. Historically, when rapidly growing human populations led to the near-shore system being heavily exploited, or when the dependence on other fisheries products were interrupted, Jamaica had relatively productive reef systems to fall back on. Whether this can be done again in the future will depend on the intent of the SES and whether feedback mechanisms are in place to signal ecological condition.

We propose mechanisms that could guide transitions away from the red trap that the SES dynamics have currently settled on. We highlight examples of countries that have used a specific intervention in order to move from an unsustainable local red-trap situation to more sustainable green-loop dynamics. We suggest that a successful transition into green-loop dynamics will strongly depend on data availability and continued monitoring of the SES. Future studies should seek to draw on different and multi-disciplinary perspectives to explore this and other interventions and test their feasibility with empirical data.

We arrived at our conclusion through using a conceptual lens that highlights the feedbacks within RL–GL concept and applying it to Jamaica's rich social–ecological coral reef history to reveal potential future pathways. These pathways need to be carefully re-considered under the light of a range of proficiencies, including political, economic and social expertise, before they can be successfully implemented. We want to highlight the practicality of how we applied the RL–GL concept to uncover missing feedbacks within complex social–ecological dynamics and encourage future studies to apply it to other systems to further advance sustainability research.

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## CONFLICT OF INTERESTS

On behalf of all authors, the corresponding author states that there is no conflict of interest.

## AUTHORS' CONTRIBUTIONS

All authors conceived core ideas and contributed critically to the design of the study; J.-C.D. acquired and analysed the data; all authors interpreted the results. J.-C.D. wrote the first draft of the manuscript, and all authors contributed critically to subsequent drafts and gave final approval for publication.

## DATA AVAILABILITY STATEMENT

All data used in this paper have already been published or archived elsewhere (see Table 1).

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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