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On the suitability of input–output analysis for calculating product-specific biodiversity footprints

Daniel Moran*, Milda Petersone, Francesca Verones

Programme for Industrial Ecology, NTNU, Trondheim, Norway

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ABSTRACT

Recently it has been estimated that one third of biodiversity threats are driven by consumer demand from outside the country in which the threat occurs. This occurs when the production of export goods exerts pressure on vulnerable populations. While population biologists have in cases been able to establish links between species threats and the causative industry(s), little has been done to trace this biodiversity footprint from the directly implicated industry out to final consumers, a step that would open a wider variety of policy responses. Here we investigate the suitability of multi-region input–output (MRIO) analysis for tracing out links between particular species threats, directly implicated industries, and the countries and consumer goods sectors ultimately driving these industries. Environmentally extended MRIO models are understood to provide reliable results at a macroeconomic level but uncertainty increases as the models are used to investigate individual sectors, companies, and products. In this study we examine several case studies (nickel mining in New Caledonia, coltan from the Democratic Republic of Congo, cut flowers from Kenya, and forestry in Papua New Guinea) in order to understand how and when MRIO techniques can be useful for studying biodiversity implicated supply chains. The study was conducted using the Eora global input–output database that documents >5 billion global supply chains. Calculating the biodiversity footprint at this level of detail, between specific threats, supply chains, and consumer goods, has not been done before. These case studies provide interesting insights in their own right and also serve to highlight the strengths and weaknesses of using input–output analysis techniques to calculate detailed biodiversity footprints. We conclude that MRIO analysis, while no panacea, can be useful for outlining supply chains and identifying which consumption sectors and trade and transformation steps can be subjected to closer analysis in order to enable remedial action.

1. Introduction

The planet is currently undergoing its sixth great extinction event (Chapin et al., 2000; Butchart et al., 2010; Dirzo et al., 2014; Tittensor et al., 2014). Species loss is occurring at a rate of two or more orders of magnitude greater than before the Anthropocene (Pimm et al., 1995), and humans and their domesticated animals currently account for >97% of terrestrial vertebrate biomass (Smil, 2002). Yet despite full awareness and considerable research into the problem of biodiversity loss there are few clear stratagems for ameliorating the situation. In terms of tractable policies, saving species seems to be proving a far more difficult goal than reducing GHG emissions. This is because protecting biodiversity is both an ecologically and an economically complex challenge. To begin with, measuring ecosystems' health is difficult. There is no clear consensus on any single best way to measure biodiversity health. Next, it is often difficult to attribute species threats to specific human activities – a necessary prerequisite for organizing any socio-political response. Then, even in cases where a policy has been established, economic and social interests often collide with protection goals (Chapman et al., 2003; Luck et al., 2004) and illegal and unreported activity thus continue to drive further species loss. Adding further to this complexity is the fact that in today's globalized economy purchasers in households, business, and governments are often far removed from the ecological impacts their consumption ultimately drives. Often consumers cannot directly see how their actions impact individual species.

It is this last point – supply chain opacity and complexity – that we investigate here. We use environmentally extended input–output analysis to evaluate the supply chains of biodiversity-implicated commodities. We present four case studies (nickel mining in New Caledonia, coltan from the Democratic Republic of

* Corresponding author. Tel.: +47 915 94 183.
E-mail address: daniel.moran@ntnu.no (D. Moran).

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Congo, cut flowers from Kenya, and forestry in Papua New Guinea) and use these techniques to try and identify clear links between a particular biodiversity threat, a causative industry, and the key supply chains leading out from that industry to final consumers of implicated products. Identifying such threat pathways allows all the actors along a supply chain – traders, companies, governments, and households – to contribute to reducing the magnitude or ecological intensity of a product's supply chain.

Using input–output (IO) techniques to trace environmentally important flows is not new. The basic techniques have been developed and refined since their introduction in the 1940s. IO is regularly used to calculate carbon footprints, trace substances of concern, and unravel the linkages between consumers and the raw resources their consumption requires (Graedel and Allenby, 1995; Graedel et al., 2002; Reck et al., 2008; Peters et al., 2012; Reck and Graedel, 2012; Graedel et al., 2013). What is new is using IO techniques to trace biodiversity-implicated commodities. In a seminal study on biodiversity footprints Lenzen and colleagues (Lenzen et al., 2012b) used IO accounting and found that one third of the species threats recorded on the IUCN's Red List of Threatened and Endangered Species were ultimately driven by consumption demand outside the country in which the threat was exerted.

Lenzen et al.'s study worked in the aggregate, looking at over 3000 individual species threats and 15,000 industries across 187 countries. In this study we use the same methods but look in depth at few selected species, industries, and trade flows. The aim is to determine whether IO methods are suitable for investigating individual species threats and related implicated product flows. Policy responses to biodiversity threats, especially when linked to traded products, will require a high level of industry and product detail, a fact recognized by the European Commission (Lammerant et al., 2014) and in the active interest in the biodiversity footprint. IO methods could also be used to bolster green supply chain and green certification programmes. With the selected case studies we seek to ask whether IO methods are appropriate, and robust enough, for studying individual species – industry – supply chain links. The case studies were selected to provide a "best case" of use of MRIO techniques to biodiversity-implicated products through supply chains. The cases were chosen for having clear links between species loss and a particular industry, and good trade data on that industry's onward flows.

This paper proceeds as follows. First, we introduce IO and related methods in Sections 2 and 2.1. Then, in Section 2.2 we introduce the case studies and establish the links between biodiversity pressure and one or more specific industries in each case. Next, in Section 3 we present numeric results from the IO and trade analysis. Finally, in Section 4 we offer discussion about the results, including on reliability. Finally, Section 5 concludes.

2. Methods

2.1. Input–output analysis and structural path analysis

Input–output tables provide a database of global trade flows, as well as production and consumption recipes. Using an IO table it is possible to identify supply chains such as: "A typical $10,000 automobile purchased in the US requires $1200 worth of Japanese steel parts, the production of which in turn require $600 worth of Chinese rolled steel, the production of which in turn requires $200 worth of Australian iron ore." The techniques of input–output analysis were originally developed by Leontief (1986), and the Structural Path Analysis (SPA) (Defourny and Thorbecke, 1984; Suh and Heijungs, 2007) used to extract individual supply chains from aggregate results, has been developed and applied extensively since then (e.g. in (Lenzen, 2003, 2006; Peters and Hertwich, 2006; Wood and Lenzen, 2009). For this study we used the Eora multi-region IO table (Lenzen et al., 2012a) which covers 187 countries with a detail of 26–500 economics sectors per country for a total of S = 15,909 sectors/goods. Countries in Eora have variable levels of detail because Eora is composited from national IO tables and the original native classifications are preserved. Eora was chosen from amongst the several global MRIO tables currently available (Tukker and Dietzenbacher, 2013) because of its superior country coverage. This is an important attribute because our study requires an MRIO table that covers even smaller economies in biodiversity hotspots.

The Leontief calculus can be used to connect final consumers with upstream biodiversity impacts. Leontief originally created his methods in order to calculate how much of a given primary resource, e.g. coal, was needed, across the entire economy, to satisfy $1 of consumer demand for a particular product. By conceptualizing pollution – or, in our case, biodiversity impacts – as a necessary input to production, the same methods can be employed to determine how much biodiversity impact was exerted to produce $1 of a particular good in that year. Input–output tables are retrospective accounts; they record the production recipe and trade volumes for prior years. Improvements in technology or changes in trade patterns can change the environmental impact of a sector in future years.

One challenge in studying biodiversity is choosing an indicator with which to measure biodiversity pressure or loss. For their study on total biodiversity impact, Lenzen et al. (2012b) quantified the biodiversity impact of a sector by using the total number of species endangered due to primary production of that sector. Since in this study our focus is on determining the suitability of MRIO methods for tracing individual supply chains, we may skip the difficult question of choosing how to measure biodiversity pressure. The important thing is to determine which sector(s) are responsible for causing pressure and we do not need to measure the intensity with which that pressure is exerted. Thus to construct the environmental satellite account for the environmentally extended MRIO analysis, all sectors are given 0 biodiversity impact, except the selected sector(s) which are given a value of 1. All numeric results, then, are expressed as dimensionless percentages of the total impact.

The Leontief method has been well explained (for overviews see Wiedmann, 2009; Kitzes, 2013; Schaffartzik et al., 2014) but we briefly reiterate it here. Using the Eora MRIO table $\mathbf{T}_{s\times s}$ documenting the monetary transactions between S sectors, the biodiversity footprint $\mathbf{F}_{1\times s}$ in terms of a particular implicated commodity, resulting directly and indirectly from spending $\mathbf{y}_{s\times 1}$ of final consumers is $\mathbf{F} = \mathbf{Q}\hat{\mathbf{x}}^{-1}(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}\mathbf{y}$, where $\mathbf{x}_{s\times 1}$ denotes sectoral gross output, the $\hat{}$operator denotes diagonalization, $\mathbf{I}_{s\times s}$ is an identity matrix, and $\mathbf{Q}_{1\times s}$ is an environmental satellite account containing the value of other resources used as input in that sector. For each case study a $\mathbf{Q}$ vector was constructed containing a single nonzero unit element flagging the environmental input to the particular sector under consideration. In this environmentally extended input–output analysis the units used in the satellite account are arbitrary; the result footprint will be expressed in the same unit as used in the satellite account. In these studies footprint was measured not according to number of species or area impacted, but merely as a share of a unit impact. The term $\mathbf{Q}\hat{\mathbf{x}}^{-1}$ contains the direct biodiversity impact of each sector's production, in terms of impact per $ gross output. The term $(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})$ (where the sub-term $\mathbf{T}\hat{\mathbf{x}}^{-1}$ is often abbreviated $\mathbf{A}$, or technical coefficients matrix) is the classic Leontief inverse. All analysis was conducted in terms of producer's prices.

By solving the Leontief inverse as a Taylor series expansion footprints can be unravelled into individual paths. We abbreviate the terms to $\mathbf{q} = \mathbf{Q}\hat{\mathbf{x}}^{-1}$ and define a technical coefficients matrix $\mathbf{A}$, expressing production recipes in each column as composition of inputs needed to produce \$1 of output, as $\mathbf{A} = \mathbf{T}\hat{\mathbf{x}}^{-1}$. We find that $\mathbf{F} = \mathbf{q}(\mathbf{I} - \mathbf{A})^{-1}$ which can be expanded into an infinite series of sums:

$$F_i = \sum_m q_{im} y_m + \sum_{lm} q_{il} A_{lm} y_m + \sum_{klm} q_{il} A_{kl} A_{lm} y_m + \sum_{iklm} q_{ij} A_{jk} A_{lm} y_m + \cdots.$$

where each term $q_{ij} A_{jk} \ldots A_{lm} y_m$ represents a supply chain starting with an expenditure y_m on a commodity produced by industry m, proceeding with an input A_{lm} by another industry l that is required by industry m to produce a commodity worth y_m. The supply chain continues via additional upstream suppliers of inputs k, and ends with a producing industry j that causes threats to species i. In particular,

- $\sum_m q_{im} y_m$ describes threats occurring directly at the place of final demand (for example because of pollutants emitted by a household),
- $\sum_{lm} q_{il} A_{lm} y_m$ describes threats facilitated indirectly through one-stage supply chains (for example because of emissions from a factory producing consumer goods),
- $\sum_{klm} q_{ik} A_{kl} A_{lm} y_m$ describes threats facilitated indirectly through two-stage supply chains (for example because of overfishing of marine species destined for processing and canning, and then finally sold),
- $\sum_{jklm} q_{ik} A_{jk} A_{kl} A_{lm} y_m$ describes threats facilitated indirectly through three-stage supply chains (for example because of habitat destruction by wheat grown for a flour mill making flour for a bakery selling bread to consumers,
- and so on.

As this is an infinite series, there are theoretically an infinite number of supply chains. However, the longest and smallest of these approach infinitesimally small magnitudes. For the Eora MRIO database, approximately 5 billion of these chains have a statistically meaningful magnitude. Structural Path Analysis is then simply an enumeration, ranking, and optional filtering of these paths.

2.2. Case studies

Here we present four case studies using IO methods to trace one flagged production sector to final consumers worldwide. First we establish, for each case study, the link between biodiversity threat and a specific causative industry(s) in that country. Then, in the Section 3, Results, with a clear link between a threat and a responsible industry established the IO and SPA methods are employed in order to trace the outputs from that industry through global production chains to end consumers. We also identify for each study the top countries consuming those biodiversity-implicated products and present some of the paths through which those implicated goods flow. Finally, in Section 4, Discussion, we discuss the results, including areas which may contribute uncertainty to the results. The selected case studies were chosen because of the availability of both good trade data to follow the resource through the supply chain, as well as clear links between biodiversity loss and a specific industry. We study coltan mining in the Democratic Republic of Congo, nickel mining in New Caledonia, cut flower production in Kenya, and forestry in Papua New Guinea (Fig. 1).

2.2.1. Nickel mining in New Caledonia

New Caledonia, an island archipelago in the south-west Pacific (Fig. 1), is a global biodiversity hotspot (Mittermeier et al., 1996; Myers et al., 2000) with extraordinary floristic diversity and high local endemism (Morat et al., 2012; Wulff et al., 2013). It has been listed as one of the most important metallophyte hotspots (Whiting et al., 2004) where plants have evolved and adapted to the metal rich ultramafic soils covering one third of the archipelago (Proctor, 2003). This unique diversity is threatened by economic activities, such as open-pit nickel mining and processing industries, causing severe environmental degradation (Pascal et al., 2008; Jaffré et al., 2010f; Wulff et al., 2013). Human-induced fires constitute a secondary threat. Since fires occur for a variety of reasons without clear evidence linking threats related to human-induced fires to production of a specific commodity we restrict ourselves to study the link between mining activity and biodiversity threats.

The unique flora of New Caledonia contains 3371 species of vascular plants, with more than 74% being endemic to the archipelago (Morat et al., 2012). Moreover, recent studies (Wulff et al., 2013; Ibanez et al., 2014) suggest that many endemic plant species have highly restricted distribution ranges, covering only one or few localities with small population numbers. This makes them inherently vulnerable to extinction. Most (60%) of the plant species are localized on ultramafic substrates (Proctor, 2003) and 90% of those are endemic to New Caledonia (Morat, 1993). Endemic species include 43 conifer species (7% of the world's total conifer diversity) (Farjon and Page, 2003), which makes the archipelago's conifer fauna one of the richest in the world. All but one of these conifer species are included in the IUCN Red List, with status varying from "least concern" (LC) to "critically endangered" (CR). All of them occur on ultramafic soils and the majority (68%) is restricted to this substrate (Jaffré et al., 2010a). Among the conifer species is the critically endangered (CR) *Araucaria nemorosa* with a small and fragmented distribution in the southern part of the archipelago occurring on only 9.8 km^2 (Kettle et al., 2007; Jaffré et al., 2010a). This species has been classified as CR due to recently revealed negative genetic effects on juvenile population and overall demographics due to habitat degradation mainly from mining activities and human induced fires (Kettle et al., 2007). None of *Araucaria nemorosa*'s range is protected. Furthermore, a new hydro-metallurgic plant is being built in the area (Jaffré et al., 2010a). The start of the mining activities in New Caledonia dates back to the second half of the 19th century with wide-scale mining establishment in the last decades of the 20th century (Ali and Grewal, 2006). The archipelago harbours between 20% and 30% of the global nickel deposits (Jaffré et al., 2010a) and is now the world's second leading producer of ferronickel (an alloy composed of nickel and iron) and one of the top suppliers of nickel ore (USGS, 2013, 2014d). The archipelago is home to some of the biggest nickel mines in the world from which the Goro nickel-cobalt mine is the largest. It is planned that the mine, will reach an annual capacity of 60,000 t nickel and 4650 t of cobalt using high-pressure acid leaching technology, which allows extracting metals from low-grade ores, but leaving huge amounts of tailings (USGS, 2014a). The capacity, however, has not yet been reached due to several incidents of acid spills from the mines, causing environmental damage and local outrage (USGS, 2012; Lefort and Burton, 2014, USGS, 2014a).

Nevertheless, mining expansion can be expected in New Caledonia since nickel and cobalt production accounts for almost 90% of the total exports (USGS, 2014a). This is largely possible due to increasing mining of low-grade deposits (Jaffré et al., 2010a), attractive tax rates, and weakly enforced environmental regulations (Ali and Grewal, 2006). Together this gives reasons for concern over the future of island's unique biodiversity, particularly species restricted to ultramafic soil. Mining activities potentially threatens the habitat and distribution of the endemic floral species through habitat destruction, fragmentation, deposition of tailings and pollution.

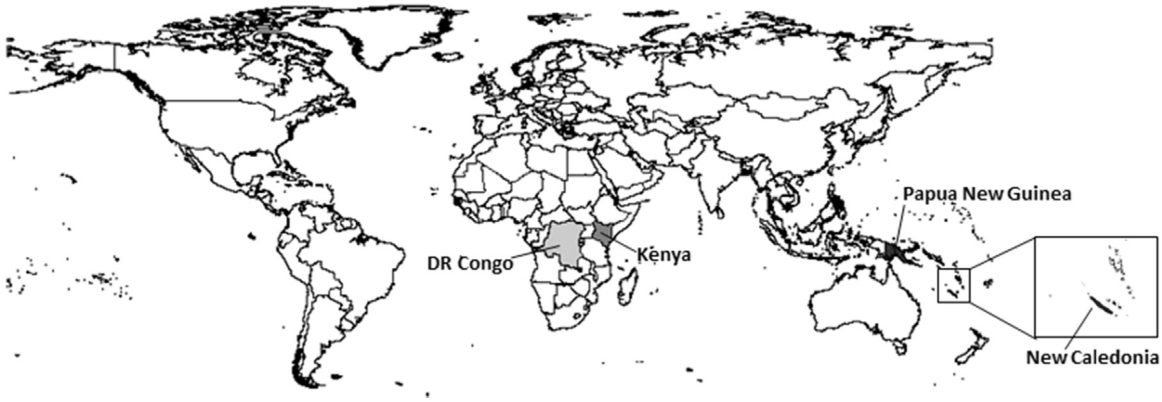

Fig. 1. Geographical locations of the four case studies in grey shades: DR Congo, Kenya, Papua New Guinea and in the blow-up New Caledonia.

2.2.2. Tantalum (coltan) mining in the Democratic Republic of Congo

The price of tantalum – a rare earth metal used in a variety of electronics – spiked in the early 2000s. The resulting gold rush for the DRCs easily-mined surface deposits was alleged to have been a major funding source for warlords during the country's civil war. The UN called coltan "the engine of conflict in the DRC" (UN Security Council, 2001 §IV.215). In addition to the human cost of this conflict mineral, illegal mining camps within several national parks decimated populations of gorillas and other endangered, edible animals. According to an investigation (Hayes and Burge, 2003) miners in one national park effectively eliminated the gorilla and elephant populations there. One investigator reported that miners moving into the park began hunting elephants, gorillas, chimpanzees, buffalos and antelopes but after one year had depleted these stocks and were eating only tortoises, birds and small animals (Redmond, 2001).

2.2.3. Flower horticulture at lake Naivasha, Kenya

Lake Naivasha, situated 80 km north-west of Nairobi in the Rift Valley of Kenya is the second largest freshwater lake in the country after Lake Victoria. It has been declared a wetland of international importance under the Ramsar Convention in 1995 and an Important Bird Area in 2001, supporting over 350 different water bird species and also harbouring a large hippo population (*Hippopotamus amphibious*; classified by the IUCN as Vulnerable) among others (Ramsar, 2012; BirdLife International, 2014). In the last decades the area around the lake has grown to become the main site of Kenya's horticulture industry, from which the principle product is cut flowers – Kenya's second most profitable export after tea. Flower farms are an important local income source and represent a major share of Kenya's export earnings in general, yet flower farms are heavily responsible for the deteriorating health of Lake Naivasha (Otiang'a-Owiti and Oswe, 2007; Mekonnen et al., 2012; Awange et al., 2013).

Although the lake has always been used by humans, socio-economic activities around the lake reached a new level in the 1990s when the cut-flower industry expanded into ≈100 km^2 of irrigated land around the lake within a decade (Harper and Mavuti, 2004). Since then, Kenya's floriculture industry, mostly located around Lake Naivasha (95% in 2005) (Mekonnen et al., 2012), has grown every year – from 11,000 t of flowers exported in 1988 to 125,000 t in 2013 (KFC, 2014).

It is estimated that human population around Lake Naivasha has expanded to 250,000, which is around ten times more than in the beginning of the boom of flower industry (Enniskillen, 2002). With expansion of social and economic activities around the lake, human impacts have increased threatening the wetland ecosystem of Lake Naivasha and its biodiversity. These impacts include habitat destruction around the lake and lake-wide papyrus decline (Everard and Harper, 2002; MacLean et al., 2003; Morrison and Harper, 2009), chemical water pollution and eutrophication due to runoff from settlements, local farming and industries (Kitaka et al., 2002; Ndungu et al., 2013), overfishing (Hickley et al., 2004), alien species introduction (Gherardi et al., 2011) and excessive water abstraction (Becht and Harper, 2002; Awange et al., 2013). The water level declines in the lake due to water abstraction has been proven to be directly linked with cut-flower exports and constitutes a major threat for the future existence of the lake and surrounding areas (Mekonnen et al., 2012; Awange et al., 2013).

The horticulture boom has provided social benefits. An estimated 90,000 direct jobs and 500,000 indirect jobs (KFC, 2014) are linked to cut-flower production, in addition to free housing, schools and hospitals provided to employees and their families. The industry provides high return in terms of revenue per unit water use.

However, the industrial farming expansion has been detrimental for biodiversity in the area. Otiang'a-Owiti and Oswe (2007) used the Living Planet Index methodology (Loh et al., 2005) to construct a composite (8 species) index of water bird health around the lake, from 1982 to 2002. Indexed to 1982 = 100%, their LPI index of bird health had declined to 40% by 2002. A study of population changes of the African Fish Eagle at the lake (Harper et al., 2002) also showed a decline from 1987 to 1999. Papyrus-vegetated area, an important water bird habitat, has substantially decreased between 1955 and 2000 (Everard and Harper, 2002).

2.2.4. Forestry in Papua New Guinea

Papua New Guinea (PNG), occupying the eastern part of the island New Guinea and surrounding islands, supports one of the world's largest and biologically and culturally richest rain forests (Brooks et al., 2006; Gorenflo et al., 2012). Covering 28.3 million hectares of land area (Shearman et al., 2009) it hosts most of PNG's unique biodiversity, which is around 7% of the world's total species (PNG 4th National Report on the CBD, 2010; Shearman and Bryan, 2011). Furthermore, it is one of the last "wild areas" left (Mittermeier et al., 1998; Sanderson et al., 2002) with many species yet to be discovered. Despite that, PNG forests have been exploited more rapidly than previously assumed (Shearman et al., 2009) and it is very likely that most of the accessible rainforests will disappear or be seriously degraded within the next two decades if current trends continue (Filer et al., 2009; Shearman et al., 2009, 2012).

The PNG forest ecosystem covers around 70% of the land, most of which is rainforest (Shearman et al., 2009). The landscape is rugged, with extensive areas reaching over 3000 m above sea level (PNG

4th National Report on the CBD, 2010) creating very diverse habitats, many of which are inaccessible. There are still many gaps in the knowledge about flora and fauna of Papua New Guinea (IUCN, 2008), therefore exact numbers of species are not known. Today 2316 of 26,318 species are assessed by IUCN (20% of them endemic), and many more are assumed to be undiscovered (e.g. 150,000 insect species are estimated to be unidentified in PNG) (Sekhran et al., 1995; IUCN, 2008; PNG 4th National Report on the CBD, 2010). More than 1060 new species, including 12 mammal species, were discovered and described on the island of New Guinea between 1998 and 2008 (WWF, 2011b).

There are many activities driving deforestation and forest degradation in PNG, including subsistence agriculture, plantation development, and mining (Shearman et al., 2009; Nelson et al., 2014). Logging, however, a large share of which is export-driven, has caused the largest part of forest change (Shearman et al., 2009). Shearman et al. compared land-cover maps between 1972 and 2002 and concluded that a net 15% of primary rain forest was cleared and an additional 8.8% degraded to secondary forest (resulting in soil depletion and increased vulnerability to fire) due to logging in PNG (Shearman et al., 2009). Lowland forest areas (65% of all PNG forests) are of particular concern, as they are more easily accessible than mountain forests and an estimated 30% has been cleared or degraded in the past 30 year period, mainly due to logging (Shearman and Bryan, 2011).

3. Results

Having established for each case study a link between biodiversity pressure and one or more specific industries in each country, we now report on the result of the input–output analysis of each of those produced commodities.

3.1. Nickel mining in New Caledonia

The threat to biodiversity on New Caledonia is related to the mining and building of a new metallurgical plant. Nickel can be found in various products ranging from pots, pans and jewellery to marine and aerospace applications. Its biggest use is as an alloying element for stainless and heat-resisting steels (Nickel Institute, 2014). Most often nickel and nickel products from New Caledonia are sent to Japan, Australia and France where they are used in steel alloys. SPA results, and a table of top consumer countries with top consumption categories (Table 1 and Fig. 2), show that most of the steel is afterwards again exported to be used in various applications in different countries. Japan, China and USA were the biggest final consumers of New Caledonian nickel in 2000, having consumed 45% of total production in 2011. The MRIO analysis shows that one final use of New Caledonian nickel is Japanese passenger cars purchased in the US, made using Japanese steels containing New Caledonian alloys. Another top value supply route of nickel to final consumer, being worth $7.9 million, shows nickel from New Caledonia used in Japan steel industry for final demand in the Chinese construction sector: "New Caledonia mining and quarrying industry → Japan pig iron products → Japan crude steel (converters) products → Japan hot rolled steel products → Final demand in China in the construction sector". Other examples from SPA of final consumers include nickeled Japanese steel alloys used in car production in Australia ($4,800,000), wires and cables in railway construction in Japan ($1,800,000), ship building in South Korea ($1,000,000) and storage battery manufacture in the US ($100,000). Notably, nickel is widely used in precious metal alloys to increase the strength, as well as for plating of inexpensive costume jewellery (Nickel Institute, 2009). A representative path for this "New Caledonia mining and quarrying industry → Japan other non-ferrous metals products → USA jewellery and silverware manufacturing industry → Final demand in USA in the jewellery and silverware manufacturing sector" is worth $400,000 of nickel and includes New Caledonian nickel embodied in jewellery consumed in USA.

Table 1
– Top final consumers, with top implicated consumption goods, of embodied New Caledonian nickel. Goods and services are domestically produced, using embodied New Caledonian nickel, unless an origin country is specified. Data are for 2011.

Top final consumers (Percent of total impact)	Top implicated final consumption goods (Percent of total consumption in the consumer country)
Japan (18%)	Non-residential construction (non-wooden) (10%); Passenger motor cars (7%); Residential construction (non-wooden) (7%); Public construction of roads (4%)
China (15%)	Construction (42%); Other special industrial equipment (7%); Motor vehicles (3%); Communication equipment (2%)
USA (12%)	Light truck and utility vehicle manufacturing (8%); Japanese Passenger motor cars (8%); Automobile manufacturing (6%); Other non-residential structures (4%)
New Caledonia (9%)	Construction (30%); Metal Products (14%); Electrical and Machinery (10%); Administration (8%)
Australia (8%)	Residential building construction (16%); Non-residential building construction (9%); Finished cars (8%); New Caledonian Mining and Quarrying (8%)
France (5%)	Construction work (22%); Motor vehicles, trailers and semi-trailers (14%); Fabricated metal products, except machinery and equipment (13%); Machinery and equipment n.e.c. (5%)
South Korea (3%)	Japanese Steel ships (15%); Public administration and defense (9%); Motor vehicles and parts (7%); Electronic machinery, equipment, and supplies (7%)
Spain (3%)	Residential buildings (13%); Civil engineering (6%); Motor vehicles (6%); Non-residential buildings (5%)
Italy (2%)	Construction work (9%); Furniture; other manufactured goods n.e.c. (9%); Machinery and equipment n.e.c. (7%); New Caledonian Metal Products (6%)
Germany (2%)	Passenger cars and parts (8%); Installations and other construction (5%); French Motor vehicles, trailers and semi-trailers (4%); Spanish Motor vehicles (3%)

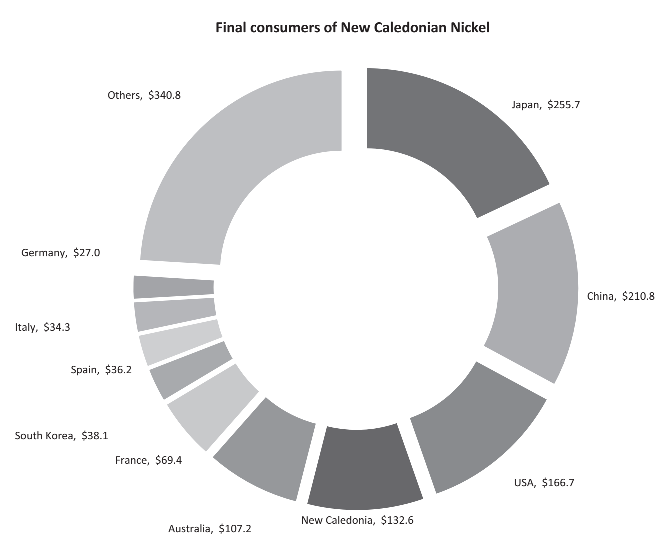

Fig. 2. Final consumers of New Caledonia nickel (direct + indirect flows). Values in million $US, for 2011.

3.2. Tantalum (Coltan) mining in the Democratic Republic of Congo

It is not difficult to establish a link between coltan mining and biodiversity loss in DRC. Most conflict coltan from DRC ultimately affected the population of gorilla, chimpanzee, African buffalo and several antelope species both through habitat destruction and fragmentation from mining and poaching by miners and other persons. However, while the overall link between mining and biodiversity loss is clear, due to poor information it is difficult to more precisely prove a link between mining and any one particular species being threatened.

We draw on a study by Moran et al. (2014) who constructed a hybrid LCA-MRIO study for columbite–tantalum (coltan) ore mined in the Democratic Republic of Congo (DRC). We include this case study not simply to repeat previous work but to highlight in the context of this paper the high level of detail possible to achieve using Hybrid MRIO techniques. Moran et al. (2014) executed a hybrid LCA-MRIO analysis by separating the DRC "Mining" sector in the Eora global MRIO into a "Coltan Mining" and "Other Mining" sector. This disaggregation step was necessary, since a straight IO analysis using the original IO table would just follow flows of "Mining" products, not separated into coltan vs non-coltan ores, and such a broad product group is too mixed to provide useful results on coltan flows. Their study used data from a range of other sources, including the UN, US Geological Survey, and an investigative report by Nest (2011), to accomplish this disaggregation and distinguish coltan flows from general DRC ore flows. With the improved MRIO in hand the Moran et al. (2014) study used the same footprinting and SPA methods as discussed above to calculate coltan footprints and identify the main supply chains conveying embodied coltan.[1]

Moran et al. (2014) traced conflict coltan to processors and refiners in the US, Germany, and Kazakhstan, where it was then sold onward, primarily for use in electronics. Germany, USA, China, UK, and Japan were identified as top final destinations of products containing DRC-sourced coltan. Coltan is used in mobile phone batteries and compact capacitors used in entertainment electronics. One representative path was "DRC → Rwanda → USA processing → USA electronic capacitor, resistor, coil, transformer, and other inductor manufacturing products → Final demand in South Korea in the radio, television, and communications equipment sector" showing US$75,000 worth of coltan (0.22% of DRC coltan mined in 2000); this path would capture flows of coltan into game console electronics and mobile phones purchased by Koreans. The study was also able to capture more obscure paths, for example: "DRC → Rwanda → USA processing → USA electronic capacitor, resistor, coil, transformer, and other inductor manufacturing products → Mexico manufacture of transport equipment industry → Final demand in Mexico in the manufacture of transport equipment sector." In this path $US 57,000 worth of coltan that leaves DRC, is used in electronics within American vehicles, which are then sold to consumers in Mexico. This path includes both physically embodied coltan (e.g. used in the electronics, airbags, ignition, antilock brake system, or corrosion-resistant bolts) and also indirect flows, e.g. when coltan is used for precision manufacturing tools which are used to build the car.

[1] Parenthetically, we shall mention an important note regarding the word *embodied*. In normal usage one would say a product contained embodied coltan if some coltan were physically present in the final product. However when used in footprint analysis the term also refers to indirect usage, for example if a product is made in a factory using coltan-alloyed machine tools.

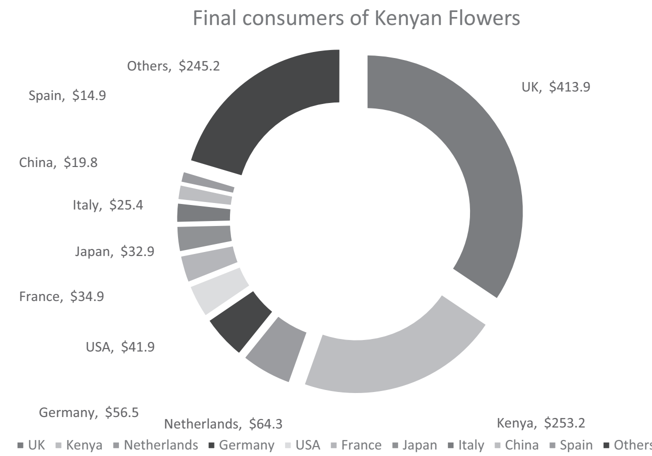

Fig. 3. Final consumers of Kenyan cut flowers (direct + indirect flows). Values in million $US, for 2011.

3.3. Flower horticulture at Lake Naivasha, Kenya

Roses are the main product of Kenya's floriculture industry, leading the rose import in the EU with a 38% market share (KFC, 2014). However, also within Kenya itself, the consumption of flowers is high. The supply of fresh flowers for the western markets/consumers is dependent upon aviation (Everard and Harper, 2002) and 90% of the fresh flowers is transported to the Netherlands (Mekonnen et al., 2012), mostly ending up in Dutch flower auctions. UK supermarkets are one major retail outlet for Kenyan flowers (KFC, 2014). Other destinations include Japan, Russia and the USA. Fig. 3 shows the top final consumers of Kenyan flowers according to the MRIO analyses. The UK, Netherlands, Germany France, and USA show up as top consumers. For this case study we do not elucidate the particular sectorwise composition of flower purchases in each consumer country. Flowers are purchased across all sectors: by consumers at shops, by restaurants, by hospitals, by businesses, etc., and the particular sector in which consumption occurs is not important since in this case policy responses would most likely target the product itself (flowers) rather than the sector in which those flowers are purchased. The horticulture contributed to a decline in the volume and surface area of the lake and also caused the concentrations of pollutants to rise. This has potentially direct negative consequences for the species in and near the lake. This example of a clear causal relationship between a single industry and an easily visible consumer product has resulted in much attention from national and international organizations (FWW and CC, 2008; Mekonnen and Hoekstra, 2010; WWF, 2011a; LNRA, 2014).

Fig. 4

In this case study, flowers from Kenya went into the Netherlands Agriculture sector but from there, in the MRIO analysis the flowers become mixed with all other Agriculture products. In this case product-specific information reported by the industry association is a better data source. Another curious finding from the case study is that Kenya itself is a major consumer of flowers. This finding reflects the data reported by the MRIO database, but the database could be incorrect.

3.4. Forestry in Papua New Guinea

Given the rapid growth and extensive area of forestry operations in PNG, and the high value of biodiversity in Papuan forests, it is not difficult to establish a connection between forestry activity and biodiversity pressure in the country. The more area is deforested or fragmented, the more species potentially lose (parts of) their habitats. Thus they may get increasingly stressed and could

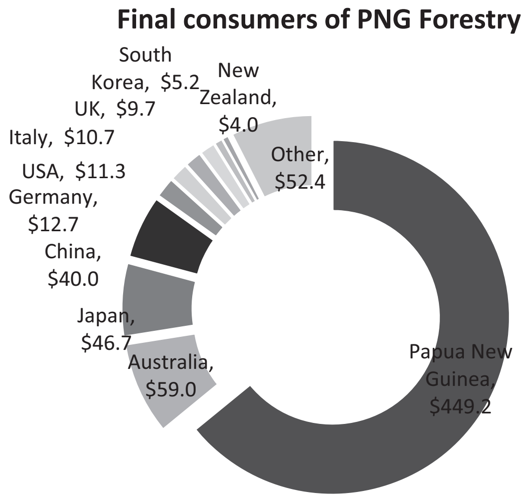

Fig. 4. Final consumers of PNG forestry products (direct + indirect flows). Values in million $US, for 2011.

potentially go extinct. Since so many species are yet to be discovered, the direct link from logging to extinction may be hard (species may already be extinct now, without having been discovered first).

Raw logs are the main exported timber commodity and account for 90% of timber exported by volume in PNG (Papua New Guinea Forest Authority, 2009). A total of 3 million m^3 of roundwood was exported from PNG in 2012, making PNG the second-largest exporter of tropical logs after Malaysia (FAO Statistics Division (FAOSTAT) 2012). Even though timber exports have been increasing for more than a decade, the timber industry, which according to Laurance et al. 'suffers from endemic corruption' (2011), generates only a small fraction (5.6%, (United Nations Statistics Division, 2012) of annual export earnings of PNG, and is dwarfed by gold, copper and platinum mining (together >50% of export earnings). Private logging companies with Malaysian ownership dominate the timber industry, further exporting raw wood for manufacturing in China, which then supplies consumers all over the world often looking for aesthetics in tropical timber rather than necessity (Papua New Guinea Forest Authority, 2009; Laurance et al., 2011, 2012; Shearman et al., 2012). Little of the added value of further processed timber ends up in PNG as almost no domestic wood processing is taking place in PNG (Papua New Guinea Forest Authority, 2009).

We find that even though China is the major export destination of PNG timber, most timber is processed and delivered onward to final consumers elsewhere. In the Final Consumers Table 2 China is only the 3rd largest foreign consumer of PNG timber, but it is also a major re-exporter. Australia and Japan are the largest consumers of PNG timber (after PNG itself), but at least one fifth ends up in Europe (Germany, Italy, UK, etc.) and the USA. Structural path analysis results show that timber, much of which is hardwood, is used in building sectors in Japan, China, Australia, New Zealand and other countries most likely for house constructions, flooring, wooden panels etc. Japan is the main producer and consumer of paper products made from PNG timber. As an example we find one path showing $300,000 of PNG timber flowing from "Papua New Guinea wood and paper industry → Japan pulp products → Japan paper products → Final demand in Japan in the newspapers sector". Another noteworthy consumption sector is USA Light Trucks: this value includes Papuan hardwoods flowing through various trade and transformation paths and ending as veneers in decorative car interior panelling. Finally, similarly to Kenyan flowers we observe that biodiversity-implicated timber enters the Chinese Sawn Wood Products sector, but there became mixed with all other sawn wood products from all other sources. Assuming that Papuan wood is used by Chinese industries at the same frequency as average sawn wood this fact is not a problem since the Papuan wood footprint will still end up in Chinese goods. However if Papuan wood entering the Chinese Sawn Wood sector faces noticeably different fates than typical wood entering the sector, this difference will not be captured well by the MRIO analysis.

Table 2
– Top final consumers, with top implicated consumption goods, of Papuan forestry products. Goods and services are domestically produced, using embodied Papuan forestry goods, unless an origin country is specified. Data are for year 2011.

Top final consumers (Percent of total impact)	Top implicated final consumption goods (Percent of total consumption in the consumer country)
Papua New Guinea (64%)	Education, Health and Other Services (17%); Public Administration (14%); Financial Intermediation and Business Activities (13%); Wood and Paper (11%)
Australia (8%)	Papuan Education, Health and Other Services (18%); Papuan Construction (11%); Papuan Retail Trade (11%); Papuan Transport (7%)
Japan (7%)	Residential construction (wooden) (16%); Residential construction (non-wooden) (9%); Non-residential construction (non-wooden) (7%); General eating and drinking places (except coffee shops) (4%)
China (6%)	Construction (48%); Educational services (4%); Public administration and other sectors (4%); Furniture and products of wood, bamboo, cane, palm, straw, etc. (4%)
Germany (2%)	Food products (16%); Papuan Agriculture (13%); Papuan Food & Beverages (11%); Installations and other construction (6%)
USA (2%)	Chinese Furniture and products of wood, bamboo, cane, palm, straw, etc. (6%); General Federal defence government services (5%); General state and local government services (5%); Light truck and utility vehicle manufacturing (3%)
Italy (2%)	Papuan Food & Beverages (36%); Food products and beverages (16%); Hotel and restaurant services (16%); Retail trade services, except of motor vehicles and motorcycles; repair services of personal and household goods (6%)
UK (1%)	Papuan Food & Beverages (6%); Papuan Hotels and Restaurants (3%); Papuan Transport (3%); UK Social work activities (3%)
South Korea (1%)	Transportation and warehousing (12%); Furniture (8%); Papuan Hotels and Restaurants (7%); Public administration and defence (7%)
New Zealand (1%)	Residential building construction (26%); Non-residential building construction (16%); Papuan Food & Beverages (4%); Civil engineering (4%)

4. Discussion

Input–output and SPA techniques have been used for many years across many applications to trace flows of environmental concern. In selecting these case studies we sought to find examples in which a specific species threat is caused by one (or a small number) of particular industries, the products of which can then be traced through international supply chains. Originally, we had hoped to find case studies with species whose population trends were being tracked by the Living Planet Index (LPI) (WWF, 2014), however we were unable to identify any species with LPI time series data that were under threat due to a small number of specific industries. Often species are under threat from an array of causes and it is difficult to implicate a particular commodity as causing a particular threat. Establishing such a link is crucial in order to continue to a supply chain analysis and imagine a consumer-oriented policy response. The macroeconomic evaluation conducted by Lenzen et al. (2012b) avoided this problem by assigning all threats, with varying degrees of probability, to all industries. This provides adequate aggregate results, but clear, defensible, threat ↔ industry links are a necessary starting point for most realistic policy responses. Even in these carefully selected case studies it is not difficult to imagine the implicated industry, or individual companies within that industry, being able to plausibly deny responsibility for any particular species threat.

In addition to the difficulty of implicating specific companies and industries there are also shortcomings in the MRIO data, even when using the most detailed available global trade database. The MRIO databases themselves may contain errors, though in general we may expect that MRIO data quality will continue to improve. IO and SPA analyses are attended by several sources of uncertainty. These sources of error have been well discussed in the literature but we shall summarize them here again as they relate to our particular question about the accuracy of IO tools for assessing product-specific biodiversity footprints. Biodiversity impacts could be mischaracterized or *mis-attributed* to the appropriate causative sector (e.g. it could be difficult to discern whether an impact associated with bamboo cultivation should be attributed to an Agriculture or Forestry Products sector). In life-cycle analysis this type of error relates to so-called system boundaries: which activities and flows should be included, or excluded, from a product's life-cycle inventory (Suh et al., 2004), and, related to this, are truncation errors in LCA assessments due to incomplete assessment of indirect flows (Lenzen, 2001). The economic data in the MRIO table itself, and individual transaction data points within it, are subject to *stochastic error*. However, recent studies (Moran and Wood, 2014) suggest that uncertainty arising from stochastic error is manageable. *Aggregation error* affects all input–output analyses: the sectors in the MRIO table are aggregated sectors and each sector may represent a bundle of goods or processes with diverse environmental profiles. This can mean that the sector as a whole is a poor approximation of its constituent flows.

Aggregation error is a well-studied topic in IO analysis (Andrew et al., 2009; Lenzen, 2011; Steen-Olsen et al., 2013) and generally is held to be a manageable problem (Alexeeva-Talebi et al., 2012; Caron, 2012), mostly to be solved by using newer, higher resolution IO tables such as Eora. Nevertheless, this issue of sectoral detail is particularly relevant for our study. Often developing economies have lower-resolution IO tables, for example reporting a single "Forestry" sector that could contain both sustainably-farmed softwood products and unsustainably harvested hardwood products. These two goods obviously have different environmental profiles, yet IO analysis treats them as a homogenous product when tracing it through trade and transformation steps. The solution is to use higher resolution IO tables if available, or to find superior data with which to split the sector into finer, disaggregated, products. This latter technique is called hybrid MRIO or hybrid LCA analysis (Suh and Huppes, 2000; Suh et al., 2003, 2004; Suh and Huppes, 2005; Suh and Nakamura, 2007; Ewing et al., 2011; Weinzettel et al., 2014). Hybrid MRIO analysis provides generally superior results, but has high data demands, on par with those of a product-specific life-cycle analysis (LCA) study. In this study we sought to examine whether macroeconomic MRIO analysis is detailed enough to provide useful information to guide more detailed studies at the product specific level. However, we found that three of the case studies (Kenya, Papua New Guinea and New Caledonia) suffered due to aggregation problems, in contrast to the case study of coltan (Congo), which used a hybrid LCA MRIO system for analysis.

Let us now turn to the individual case studies and what lessons may be learned from each.

In the case of nickel mining in New Caledonia it is clear that open-cast mining and associated land use change is driving threats to endemic metallophyte species. However fires, lit to clear land for a variety of reasons, also pose a threat, although we were unable to implicate any particular commodity as responsible for threats from fire. Several species are classified as Critically Endangered because of mining activity, however better published time series data would help to more clearly establish a temporal connection between declining species health and rising mining activity. Finally, the trade analysis does provide some useful results highlighting key consumers of embodied New Caledonian nickel and some key flow paths. The data error in the MRIO database, reporting negligible flows from New Caledonia to France, does call into question the validity of the chosen MRIO for this trade analysis.

In the case of the flower industry around Lake Naivasha again it is not difficult to establish a causative link between the rise of horticulture and the decline of water bird and other species at the lake. The MRIO trade analysis, however, is less helpful since many Kenyan flower exports arrive into a broad "Netherlands Agriculture" sector where they become mixed with many other goods before being sent onwards to further destinations. While the results clearly show that, in aggregate, flowers and many agricultural goods are re-exported out of the Netherlands, improved data, in this case from an industry association, was needed in order to trace this flows more finely.

Papua New Guinea is known to be a biodiversity hotspot, yet quantitative measures of biodiversity health there remains lacking. The extensive, and growing, forestry industry is clearly a major threat driver and thus Papuan timber products are implicated in biodiversity loss.

Finally, as in the other cases, in the coltan study there is a clear link between a specific industry and biodiversity pressure. In the trade analysis the coltan study unquestionably benefited from the superior, detailed, trade data added by the hybrid LCA-MRIO analysis. This indicates that hybrid LCA-MRIO techniques may be a good approach for developing product-specific biodiversity footprints. Much of the trade data is provided by the base MRIO, but by adding key elements of additional, more detailed data, even if based on models or assumptions, can help increase the accuracy and reliability of the final result. While product-level biodiversity footprints based on hybrid LCAs will likely remain only initial estimates for some more years, these techniques in terms of research time hybrid LCA methods can provide good results with work on the order of single person-months.

In general, the limiting factors in MRIO analysis for biodiversity threats are the spatial detail, economic sectoral detail, and good links between threats and implicated industries. Biodiversity information is scarce in several ways: in many world regions there is still a lack of knowledge of species presence, even if they constitute biodiversity hotspots. Also, as this is a very complex topic, the actual, direct threats affecting individual species communities are often unknown, making it hard to find robust species-threat links. However, as ecology and biology, as well as economic studies, advance, we are confident that the relevant data will become available in future, allowing for an effective tracing of biodiversity related impacts of specific industries throughout the world economy.

5. Conclusions

These case studies provide interesting insights into the challenges of connecting specific industries to particular biodiversity threats. They also highlight the possibilities, and difficulties, of tracing these commodities through supply chains, in order to calculate detailed biodiversity footprints. Despite the challenges, IO techniques can be highly useful for outlining supply chains and identifying key consumption sectors, and this in turns can help prioritize how and where further research is needed in order to provide robust, detailed data usable by governments or companies to start forming economic responses beyond the point of immediate impact. IO may be highly suitable for such initial screening given its relatively low cost: with an MRIO database in hand, calculating a biodiversity footprint is relatively simple and does not involve the months of additional work that a more in-depth LCA or similar study requires. Green labelling and certifications, trade controls, corporate engagement, and sustainable purchasing have all been shown to be useful consumption-oriented tools for alleviating environmental pressure by reducing demand for implicated products. IO analysis of product-specific biodiversity footprints can provide a starting point for developing such measures.

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