Analysing Latin American and Caribbean forest vulnerability from socio-economic factors

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\textbf{ABSTRACT}
Latin American and Caribbean (LAC) forest cover reduced by 9\% from 1990 to 2015, affecting biodiversity, climate change mitigation and ecosystem service functionality. These losses are caused by a myriad of interconnected, interdependent and often socio-economic processes, which forest vulnerability metrics largely ignore in their assessments. To address this, we develop the Deforestation Vulnerability Index (DVI) to identify spatial and temporal patterns of forest vulnerability from socio-economic processes. Composed of 13 socio-economic indicators, the DVI was applied to 24 LAC countries, and three provincial (sub-national) examples for the period 2000–2010. The DVI showed that vulnerability declined in more than 60\% of countries, due to governance improvements and reductions in agricultural expansion. Provincial application of the index showed provinces to be more vulnerable than countries, due largely to higher economic dependence upon agriculture. Observed vulnerability reductions, whilst deforestation continues, may demonstrate a lag between socio-economic improvements and subsequent deforestation reductions, or the effects of omitted or unidentified vulnerability indicators. The DVI represents a simple, yet effective tool whose outputs could be used by policy-makers and stakeholders to source vulnerability at the scale of application, whilst assisting in directing reactive and responsive sustainable forest management strategies and decision-making.

\section{1. Introduction}
Global forest area declined by 5.2\% from 1990 to 2015 (FAO 2015a), however, this deforestation was not evenly distributed, with hotspots like Latin America and the Caribbean (LAC) seeing losses of more than 9\% during the same period (FAO 2015a). These forest losses have been linked with inhibited climate change mitigation potential (Smith et al. 2014; FAO 2015b), biodiversity losses (Peres et al. 2010; Pereira et al. 2012; Haddad et al. 2015), and degraded forest provisioned ecosystem services (Spracklen et al. 2012; Boysen et al. 2014; Brienen et al. 2015).
Deforestation follows temporal (Mather 1992; Köthke et al. 2013) and spatial patterns (Angelsen 2007), with the forces behind these patterns elegantly articulated as proximate causes and underlying drivers (Geist and Lambin 2002). Proximate causes being direct human activities such as agricultural (including pasture) expansion (Guida-Johnson and Zuleta 2013), expansion of infrastructure (Hosonuma et al. 2012) and wood extraction (Echeverria et al. 2008). Whereas underlying drivers are social processes that include but are not limited to: population growth (Scricciu 2007), increased immigration (Huang et al. 2007), increased population density (Bonilla-Moheno et al. 2012), growth and globalisation of commodity markets (Asner et al. 2013), poor governance (Verburg et al. 2014), presence of democracy (Didia 1997), land tenure insecurity (Paneque-Gálvez et al. 2013) and agricultural technology development (Gasparri and Grau 2009). The consequences of long-term exposure of forests to these diverse and multi-scalar socio-economic processes are the deforestation rates highlighted by the FAO (FAO 2015a).

Turner et al. (2003) define vulnerability as the harm experienced from exposure to a hazard(s). Applying such a definition to the process of deforestation and its identified drivers and causes suggests the vulnerability of forests exposed to these processes. The importance of considering socio-economic factors and how their interactions drive forest vulnerability is important to improve our understanding of global forests (GIZ 2013; Varela-Ortega et al. 2014). Although metrics of forest vulnerability have been developed for hazards including climatic conditions (Allen et al. 2015; Mildrexler et al. 2016) and fire (Nurdina and Risdiyanto 2015; Amalina et al. 2016), they are not yet able to directly quantify and incorporate the vulnerability of forests to socio-economic processes in a singular indicator or metric. This suggests that the hazards of socio-economic processes upon forests have yet to be fully explored and quantified in terms of a singular metric. Beroya-Eitner (2016) highlights the utility of such indicator (and index) development in vulnerability research in providing concise and easily understood information.

As a means of encouraging greater inclusion of socio-economic factors in forest vulnerability research, we aim to develop a socio-economic based indicator: the Deforestation Vulnerability Index (DVI). This index will be applied to LAC countries due to: the high levels of deforestation seen there over multiple decades, the global importance of these forests for ecosystem service functionality, and the wealth of available deforestation literature dedicated to this region. Following Kissinger et al. (2012) and their insistence on the importance of analysing deforestation at multiple scales, we will apply the index at the national scale and on three sub-national (provincial) examples. Application at multiple scales and periods will demonstrate the spatial and temporal potential of the DVI for highlighting patterns of vulnerability derived from exposure to socio-economic processes, whilst establishing the potential of the index as tool for facilitating reactive policy and decision-making for forest management.

2. Material and methods

A schematic representation of the methodology applied in the development of the DVI is presented in Figure 1. The DVI follows a standardised method of index calculation (García de Jalón et al. 2014; Naumann et al. 2014).
2.1. Identification of factors responsible for forest vulnerability

We concentrated our analysis and the development of the index using socio-economic drivers or causes of deforestation previously identified within LAC countries. To identify potential indicators of vulnerability, an extensive literature review was performed covering over 100 peer-reviewed articles that considered the factors and processes behind deforestation in LAC countries (Table 1). These factors and processes were then incorporated, where possible, as indicators within the index.

The identification of indicators was further enriched using information gathered during local stakeholder workshops performed in 2013 (Varela-Ortega et al. 2014) in the Province of Guarayos (Bolivia), Tapajós National Forest (Brazil), and Cuitzmala River Basin (Mexico) as part of the EU funded project ROBIN (Role Of Biodiversity In climate change mitigatioN) (http://robinproject.info/home/). These workshops invited stakeholders (politicians, researchers, technicians and local community groups) to describe and map local environmental and socio-economic changes using the qualitative and semi-quantitative integrated methodology Fuzzy Cognitive Mapping (Kosko 1986). In each workshop deforestation was identified as the most important process occurring within each area, with an array of factors and processes identified as drivers (Varela-Ortega et al. 2014). The inclusion of this stakeholder-based information not only enriches the analysis by offering a multi-scale perspective of deforestation, but also demonstrates the potential and opportunity for incorporating stakeholder-derived information within the development of a vulnerability metric. Processes such as agricultural expansion, immigration, soybean demand, infrastructure expansion, uneffected policy, and poor governmental coordination were identified by both the literature and stakeholders as causal factors of deforestation (Table 1).
| Driver/cause of deforestation | Country(ies) where Identified | Scale of research | Examples of articles | Examples of methodologies used in identification | Identified in stakeholder workshop | Country(ies) where Identified |
|-------------------------------|--------------------------------|------------------|----------------------|-----------------------------------------------|----------------------------------|--------------------------------|
| Agricultural expansion       | Argentina, Bolivia, Brazil    | National, Provincial | Macedo et al. 2012; Müller et al. 2012; Richards et al. 2012; Guida-Johnson and Zuleta 2013; Paneque-Gálvez et al. 2013; Verburg et al. 2014 | GIS analysis, field survey, census analysis, econometric analysis | Y                                | Bolivia, Brazil and Mexico    |
| (incl. grazing expansion)    |                                |                  |                      |                                               |                                  |                                |
| Currency exchange rates      | Argentina, Bolivia, Brazil, Peru | Provincial, Provincial | Gasparri and Grau 2009; Rudel and Roper 1997; Angelsen and Kaimowitz 1999; Killeen et al. 2008; Southworth et al. 2011; Aide et al. 2013 | GIS analysis, field survey | N                                |                                    |
| Economic development         |                                |                  |                      |                                               |                                  |                                |
| Education level              | Belize, Haiti, Mexico         | National         | Chowdhury 2006; Alix-Garcia 2007; Dolisca et al. 2007; Wyman and Stein 2010 | Community survey, econometric analysis | Y                                | Mexico                          |
| Exchange rates/ Currency     | Bolivia, Paraguay             | National         | Richards et al. 2012 | Economic model | N                                |                                    |
| values                       |                                |                  |                      |                                               |                                  |                                |
| Forest cover                 | Panama                        | Local            | Rudel and Roper 1997; Sloan 2008 | GIS survey, household survey | N                                |                                    |
| Gold prices                  | Peru                           | Local            | Swenson et al. 2011; Fearnside 2001; Steininger et al. 2001; Killeen et al. 2007 | GIS analysis, Policy review, GIS analysis | N                                |                                    |
| Immigration                  | Bolivia, Brazil               | Provincial       | Wyman and Stein 2010; Southworth et al. 2011; Bottazzi and Dao 2013; Perz et al. 2013; Barber et al. 2014 | GIS analysis, censuses analysis, Field analysis, community surveys | Y                                |                                    |
| Infrastructure development   | Belize, Bolivia, Brazil, Peru | Provincial       |                      |                                               |                                  |                                |
| **International soybean demand** | Argentina, Brazil | Local, Provincial | Zak et al. 2008; Gasparri and Grau 2009; Walker et al. 2009; Barona et al. 2010; Arima et al. 2011; Verburg et al. 2014 | Economic modelling, GIS analysis, and literature review | Y | Brazil, Mexico |
| **Land prices** | Costa Rica | Provincial | Roebeling and Hendrix 2010 | Economic modelling | N |
| **Land tenure** | Bolivia, Brazil, Ecuador, Nicaragua, Peru | Provincial, National | Liscow 2013; Paneque-Gálvez et al. 2013; Perz et al. 2013; Holland et al. 2014 | Census analysis, community survey, econometric analysis, GIS analysis | Y | Bolivia |
| **Mismanaged and unenforced policy** | Bolivia, Brazil, Mexico | Local, Provincial | Durán et al. 2011; redo et al. 2011 and Verburg et al. 2014 | Economic modelling, field survey, GIS analysis | Y | Bolivia, Brazil |
| **Population density** | Brazil, Colombia, Mexico | Local, Provincial | Armenteras et al. 2006; Kirby et al. 2006; Bonilla-Moheño et al. 2012 | GIS analysis | N |
| **Population growth** | Argentina, Brazil, Haiti, Mexico | Provincial | Cropper and Griffiths 1994; Angelsen and Kaimowitz 1999; Dolisca et al. 2007; Porter-Bolland et al. 2007; Grau et al. 2008; Perez-Verdin et al. 2009 | Economic modelling, community survey, GIS analysis | Y | Brazil |
| **Poor/ Uncertain policy** | Continent wide | Provincial, National, Continental | Fearnside 2001; Culas 2007; Zwane 2007; Gasparri and Grau 2009; Redo et al. 2011; Paneque-Gálvez et al. 2013 | Econometric analysis, field survey, GIS analysis, household survey policy review | Y | Mexico |
| **Weak and poorly co-ordinated Governmental institutions** | Continent wide | Provincial, Continental | Bulte et al. 2007; Culas 2007; Barsimantov and Navia-Antezena 2012 | GIS analysis, field survey, econometric analysis | Y | Bolivia, Brazil |
2.2. Selection of national indicators and data collection

National data were sourced for 24 countries including all Latin American countries, with the exception of French Guiana due to a lack of data, and the bigger island nations of the Caribbean. Data were sourced from the FAO, the UNDP and the World Bank for the years 2000, 2005 and 2010 (coinciding with releases of the FAO: Forest Resource Assessment). The use of such international sources of data ensures: consistency, that the results can be replicated, and that the methodology can be reproduced and expanded when new data becomes available.

Thirteen factors and processes were included as indicators of vulnerability within the index (Table 2). Indicators were chosen based upon data consistency and availability, accounting for why only a limited number of potential indicators identified in Table 1 were included.

2.2.1. Provincial scale index development

To test its multi-scalar applicability, the DVI was also applied on 3 provincial scale examples (coinciding with the provinces of the ROBIN stakeholder workshops): the Department of Santa Cruz (Bolivia), the State of Pará (Brazil) and the State of Jalisco (Mexico). Where possible, indicators used in the provincial index were identical to those of the national index (Table 2). GDP (Price Purchasing Parity) per capita was unobtainable at the provincial scale; therefore we used provincial GDP (constant 2005 USD (United States Dollar)) data. National governance data were applied at the provincial scale, as no sub-national data were available. The majority of available provincial data were found to be for the period 2008–2011. To address this, we developed the provincial index only for the year 2010.

To compare provincial and national results we also collected national scale data for the aforementioned provincial index indicators. Data were collected for all 24 countries. To

Table 2. List of 13 indicators of vulnerability selected for the index. Indicators selected based upon literature review, stakeholder workshops, and data availability. Land area defined as total country area minus standing water.

| Indicator | Description | Source |
|-----------|-------------|--------|
| Gross Domestic Product (GDP) per Capita Purchasing Power Parity (PPP) | Per capita value of products and services produced | World Bank |
| Growth in agriculture value added to GDP | Annual value added to GDP from agricultural sector | World Bank |
| Soybean production value (1000 USD) | Soy production multiplied by national producer prices | FAO Stat |
| Forest area | Percentage of total national land area | FAO Stat |
| Agricultural area (incl. pastures) | Percentage national land area devoted to agriculture | FAO Stat |
| Agricultural area Growth (incl. Pastures) | Annual expansion in area devoted to agriculture | Own Formulation |
| Population density | People/sq.km of land Area | World Bank |
| Population growth | Annual national population growth | World Bank |
| Human development index | Health, education and standard of living factors | UNDP |
| Political stability | Probability of political instability and violence | World Bank |
| Government effectiveness | Quality of public services, the civil service and its independence | World Bank |
| Regulatory quality | Formulation and implementation of sound policies and regulations | World Bank |
| Road density (km/100km2) | Ratio of the length of the country’s road network to the country’s land area | World Bank |
reduce the potential of exaggerated vulnerability results stemming from normalisation (see Section 2.3) over a small data-set (3 provinces and 3 countries), we normalised the provincial index indicator data using data for all 24 countries and the 3 provinces. Comparative analysis between national and provincial results is presented only between the 3 analysed provinces, and their respective countries.

Provincial data were sourced from national censuses or statistical data banks, including: the Instituto Nacional de Estadística (INE 2011) of Bolivia, Instituto Brasileiro de Geografia e Estatística (IBGE 2010) of Brazil, the Instituto Nacional de Estadística y Geografía (INEGI 2010) and Servicio de Información Agroalimentaria y Pesquera (SIAP 2010) of México. National data were sourced from the UNDP, World Bank, and FAO.

2.3. Calculating the forest vulnerability index

The 13 indicators selected for developing the index (Table 2) were normalised to ensure identical value ranges (0–1). Normalisation of indicators (Equation 1) considered the maximum and minimum value of each indicator across all countries (and provinces).

\[
Rx_{ij} = \frac{x_{ij} - \text{Min } x_i}{\text{Max } x_i - \text{Min } x_i}
\]  

(1)

Where \(Rx_{ij}\) is the normalised value of vulnerability contributed by the \(i\)th indicator in country \(j\), \(x_{ij}\) is the non-normalised numerical value of the \(i\)th indicator in the \(j\)th country, and \(\text{Min } x_i\) and \(\text{Max } x_i\) are the minimum and maximum values of the \(i\)th indicator across all countries.

From both the literature and workshops, it was clear that increases in certain factors have inhibitory effects upon deforestation: Human Development Index (HDI) (Jha and Bawa 2006; Varela-Ortega et al. 2014), GDP per Capita (PPP) (Angelsen and Kaimowitz 1999; Kerr et al. 2004; Varela-Ortega et al. 2014), political stability (Fearnside 2003; Rodrigues-Filho et al. 2015), governmental effectiveness (Didia 1997; Redo et al. 2011; Barsimantov and Navia-Antezena 2012; Varela-Ortega et al. 2014), and regulatory quality (Verburg et al. 2014; FAO 2015b). Therefore, to incorporate these potentially inhibitory effects, these indicators were normalised as shown in Equation 2.

\[
Rx_{ij} = 1 - \frac{x_{ij} - \text{Min } x_i}{\text{Max } x_i - \text{Min } x_i}
\]  

(2)

Where \(Rx_{ij}\) is the normalised value of vulnerability contributed by the \(i\)th indicator in country \(j\), 1– inverts the normalised values to put them on the same scale as in Equation 1, so that higher values represent higher vulnerability, \(x_{ij}\) is the non-normalised numerical value of the \(i\)th indicator in the \(j\)th country, and \(\text{Min } x_i\) and \(\text{Max } x_i\) are the minimum and maximum values of the \(i\)th indicator across all countries.

All normalised indicator values \((Rx_{ij})\) ranged from 0 (lowest vulnerability) to 1 (highest vulnerability). The final index was calculated using Equation 3, where each normalised indicator value (Equations 1 and 2) was multiplied by a respective indicator weight, with the sum of these 13 weighted indicator values providing the national (and provincial) vulnerability value.

\[
DVI_j = \sum_{i=1}^{13} Rx_{ij} W_i
\]  

(3)
Where \( DVI_j \) is sum of all weighted indicators in \( j \)th country, \( Rx_j W_l \) is the weighted vulnerability contributed by the \( i \)th normalised indicator in the \( j \)th country, multiplied by the \( l \)th weighting scheme.

### 2.4. Weighting the index

Arrow (1963) suggests that there remains to be one recognised means of weighting an index. To address this, we applied two weighting schemes (expert and stakeholder). The expert weight was developed from a survey completed by 22 experts from the ROBIN project, which requested judgment on a scale of 1–5 the weight of influence that each indicator (Table 2) has in relation to deforestation. The expert weight was applied to both the national and provincial indices, as surveyed experts were familiar with the provinces included within the analysis, as well as the wider scale processes behind deforestation across LAC countries.

The stakeholder weight was developed from the stakeholder workshops of ROBIN (Varela-Ortega et al. 2014), with those factors identified and linked to deforestation forming the foundation of this weight. We used the number of times a factor was mentioned as driving deforestation in each workshop, multiplied by this factor’s relative importance in relation to deforestation (based upon stakeholder voting) (Varela-Ortega et al. 2014). These values were then converted into a proportion of the sum values for the 13 indicators. Using this methodology we developed three stakeholder weights, one for each province. As part of the provincial index these stakeholder weights were only applied to the province and country where they were developed.

We also developed and applied an equal weight, which gave each indicator the same proportional weight of 0.08 (1 divided by 13). However, the results from this weighting were not found to be statistically different \((p = 0.89)\) from the expert weight, therefore the results are not presented.\(^1\)

The weighted DVI values are relative for all countries, ranging from 0–1 with 0 representing no vulnerability, and 1 extreme. Jenks natural breaks were used (Jenks 1967) in defining 5 categories of vulnerability: low (0–0.22), moderate (0.22–0.35), vulnerable (0.35–0.45), high (0.45–0.54) and extreme (0.54–1).

### 2.5. Robustness and sensitivity of the index

The robustness of the DVI was assessed through sensitivity analysis, which evaluated how uncertainty in input indicators propagated through the structure of the index (OECD 2008). The main source of uncertainty within the DVI was the method of weighting and how this might affect the output. Thus, the sensitivity analysis focused on the uncertainty associated with weighting by assessing its impact on the DVI result.

A series of Monte Carlo experiments were performed to assess the contribution of uncertainty to the variance in the final index values. The sensitivity of the index to the weighting was performed by computing 1000 outputs of the index using random weights generated from probabilistic density functions within the index calculation (García de Jalón et al. 2014; Naumann et al. 2014). This analysis was performed only for 2010 data.
3. Results

3.1. Indicator weighting results

The results from the expert survey (Table 3) found that experts consider governance indicators, agricultural growth, and road density as the most influential indicators in driving deforestation. Results from the stakeholder weight show similar findings with governance indicators and agricultural area growth found to be particularly important.

3.2. The national index

The DVI under expert weighing (Figure 2) suggests relative stability of vulnerability across most LAC countries from 2000–2010 (National DVI results available in Table S1). Despite this perceived stability, more than 60% of countries saw vulnerability decline, with Argentina, Costa Rica, Haiti, Honduras and Venezuela being notable exceptions. The analysis also revealed a continental wide spike in vulnerability in 2005 (Figure 2(b)), where more than 80% of countries saw vulnerability increase, before declining again (Figure 2(c)). The percentage change in vulnerability during the period 2000–2010 is shown in Figure 2(d). This demonstrates that vulnerability reduced marginally in Amazonian countries including in Bolivia (−4%) and Brazil (−6%), whilst also highlighting the difference in vulnerability change in neighbouring countries. Chile (−44%) and Argentina (+29%) were found to be on the extremes of vulnerability change during the analysed period.

To tease out the source of identified changes to vulnerability (Figure 2), Figure 3 presents the weighted vulnerability values for each of the 13 DVI indicators. The results for 2000 (Figure 3(a)) appear relatively evenly spread across the indicators, with governance and agricultural indicators being slightly elevated. For example, in Chile growth in agricultural value added to GDP contributed to vulnerability, whilst in Cuba regulatory quality contributed most to vulnerability, and in Jamaica road density contributed most heavily. In 2005 (Figure 3(b)), the continental wide increase in vulnerability is observed, and can be sourced

Table 3. Results from expert survey and stakeholder workshops. These results were applied as weights within the Deforestation Vulnerability Index. Expert weights derived from surveys sent to experts from the ROBIN project, and stakeholder weights from stakeholder workshops performed as part of the ROBIN project. Values have been transformed to be proportions of 1.

| Indicator                              | Expert weight | Bolivia | Brazil | Mexico |
|----------------------------------------|---------------|---------|--------|--------|
| GDP per Capita (PPP)                   | 0.08          | 0.00    | 0.01   | 0.01   |
| Growth in agriculture value added to GDP | 0.07          | 0.00    | 0.05   | 0.05   |
| Soybean production value               | 0.08          | 0.00    | 0.01   | 0.05   |
| Forest area                            | 0.07          | 0.00    | 0.00   | 0.01   |
| Agricultural area                      | 0.06          | 0.00    | 0.00   | 0.00   |
| Agricultural area growth               | 0.09          | 0.22    | 0.03   | 0.14   |
| Population density                     | 0.07          | 0.00    | 0.00   | 0.00   |
| Population growth                      | 0.08          | 0.00    | 0.02   | 0.00   |
| Human development index                | 0.08          | 0.04    | 0.01   | 0.05   |
| Political stability                    | 0.07          | 0.00    | 0.00   | 0.00   |
| Government effectiveness              | 0.08          | 0.19    | 0.53   | 0.57   |
| Regulatory quality                     | 0.09          | 0.55    | 0.31   | 0.07   |
| Road density                           | 0.09          | 0.00    | 0.03   | 0.05   |
to agricultural area growth (with changes in Honduras being particularly great), along with changes to the governance indicators, specifically regulatory quality.

The tail of the vulnerability spike can be seen in Figure 3(c), with agricultural area growth lower than in both 2000 and 2005 (exceptions include Suriname), coupled with simultaneous reductions in vulnerability from governance indicators.

3.3. The provincial index

The results of the provincial DVI are shown in Figure 4, where in each province vulnerability under both weighting schemes was higher than the national results. Despite provinces being
Figure 3. Weighted vulnerability values for the Deforestation Vulnerability Index (DVI) indicators under expert weighting. (a) Indicator vulnerability for the year 2000. (b) Indicator vulnerability for the year 2005. (c) Indicator vulnerability for the year 2010. Bluer colours represent greater weighted vulnerability.
in many cases within the same vulnerability category as the national results, the actual DVI values were distinct (See Table S2). Application of the stakeholder weight (Figure 4(b)) results in a notable increase in vulnerability compared with the expert weight (Figure 4(a)). In Bolivia, application of the stakeholder weight increased vulnerability by two categories compared to the expert weight, whilst for the department of Santa Cruz it increased by one, showing the differential effects of the two weighting schemes. In Jalisco, vulnerability increased by a single vulnerability category, compared to the expert weight.

Under expert weighting (Figure 4(a)) each province was found to be at least 15% more vulnerable than the national value. Whereas, under stakeholder weighting (Figure 4(b)) Pará was found to be 9% more vulnerable than Brazil, Jalisco 22% more than Mexico and Santa Cruz 24% more than Bolivia. National results for Figures 2 and 4 differ slightly due to use of different GDP data (see Methods).

Sources of vulnerability in the provincial index are shown in Figure 5, under expert weighting (Figure 5(a)) and stakeholder weighting (Figure 5(b)). Under expert weighting (Figure 5(a)), vulnerability across the provinces and countries is concentrated in agricultural area growth, especially for Santa Cruz and Pará. GDP also contributes heavily to vulnerability in Bolivia, Santa Cruz, and Pará suggesting the impacts of relatively weak national and provincial economies, with Santa Cruz also especially vulnerable to high population growth rates. As with the results demonstrated in Figure 3, vulnerability can also be attributed to poor governance factors with political stability especially important in Mexico (and Jalisco), whilst

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**Figure 4.** Provincial Deforestation Vulnerability Index (DVI) values for the year 2010. Results presented are for analysed provinces (Pará, Santa Cruz, and Jalisco) and their respective countries, under the conditions and data of the provincial index. National results developed using national data for provincial index indicators. DVI indicator values were normalised using all 24 countries’ and 3 provinces’ data to reduce exaggerated results. Only analysed provinces and their respective countries are presented as stakeholder weighting could not be generated for all 24 countries. (a) DVI for selected provincial examples and their respective countries under expert weighting. (b) DVI for selected provincial examples and their respective countries under stakeholder weighting.
Figure 5. Weighted vulnerability values for provincial Deforestation Vulnerability Index (DVI) indicators. (a) Indicator vulnerability under expert weighting. (b) Indicator vulnerability under stakeholder weighting.
regulatory quality contributes to forest vulnerability in Bolivia (and Santa Cruz). In contrast, the results from the stakeholder weighting (Figure 5(b)) highlight that vulnerability concentrates in governmental effectiveness and regulatory quality for all countries and provinces, with agricultural area growth to a lesser extent also an important contributor.

### 3.4. Robustness and sensitivity analysis results

The sensitivity analysis helped to identify the robustness of the national index to the application of random weights, whilst identifying the sensitivity of countries to weighting using Monte Carlo analysis (Figure 6). In general, the values of the DVI show similar levels of dispersion for each country, with most countries having DVI values around 0.4. Haiti and Chile represent the extremes of the DVI. The overlaid dots represent the outputs values from the DVI for each country under expert weighting for the year 2010, which are located near the median of the Monte Carlo analysis, and are entirely within the 25–75 percentiles.

An analysis of variance (ANOVA) on the results from Figure 6 found that national DVI values were significantly different ($p < 0.001$). Furthermore, application of pairwise $t$-tests to all country combinations demonstrated that the majority are significantly different (See Table S3). The results of Belize and Bolivia ($p = 0.69$) and Guyana and Suriname ($p = 0.66$) were amongst the handful found not to be significantly different.

### 4. Discussion

We have highlighted the potential for the development and application of a robust metric for spatially and temporally quantifying forest vulnerability to socio-economic factors across Latin America and Caribbean countries during the period 2000–2010. Application of the DVI
also demonstrated how both expert and stakeholder derived information can be incorporated in such a metric.

Application of the DVI across LAC countries highlighted widespread decreases in vulnerability from 2000 to 2010. These declines were sourced to reductions in agricultural area growth and improvements in governance. Nepstad et al. (2014), Rodrigues-Filho et al. (2015), and Gibbs et al. (2015) all demonstrate how such governance improvements, coupled with social and supply chain initiatives have been implicated in long-term trends of reduced deforestation, and limiting agricultural area growth. Müller et al. (2014) and Hoiby and Zenteno-Hopp (2014) suggest that little progress can be made in conserving forests if policies are subject to poor governance or if policy conflicts exist, highlighting the fundamental importance of strong governance.

The findings from the DVI suggest that political focus on improved governance could offer a route for reducing global vulnerability and deforestation. However, before up-scaling our continental specific findings to a global context, it would be necessary to spatially expand the DVI to a global scale. Such expansion could help to clarify whether the identified trends are continentally specific, or are indicative of global vulnerability trends. Furthermore, it could help to highlight whether vulnerability indicators are globally consistent in terms of their importance, whilst offering an important point of comparison with other regions suffering high levels of deforestation.

A further product of the DVI was the identification of a vulnerability peak in 2005, attributed to a continent wide reduction in governmental efficacy, political stability and regulatory quality (World Bank 2013). Analysis of election data offers a potential explanation, with the period 2004–2006 seeing continent wide legislative or presidential elections (University of Texas 2010). Electoral periods have been previously characterised by increased deforestation, where deforesters anticipate that elections will bring relaxation in enforcement and or amnesties for previous deforesting (Fearnside 2003; Rodrigues-Filho et al. 2015). This peak may be further explained by a wide-scale increase in agricultural area growth, which could be associated in many cases to soy price increases seen cross the continent in 2004, which may have encouraged greater soy production and conversion of forest to croplands in 2005, consistent with previous links between commodity markets, prices, and deforestation (Zak et al. 2008; Gibbs et al. 2010).

The multi scale application of the DVI supports not only the concept of complexity and variability at sub-national levels (Simane et al. 2016), where provincial examples showed disparate vulnerability compared to the national results, but also the multi-scalar flexibility of the methodology. Both Pará (Brazil) and Santa Cruz (Bolivia) are found on the agricultural frontier and can be characterised as having high levels of economic dependence upon agricultural activities (IBGE 2010; INE 2011). This may explain why in these provinces vulnerability was found to be considerably higher than the national value, with economic alternatives to agriculture being limited and higher rates of population growth placing greater pressure on provincial forests.

Smith et al. (2014), OBT (2014), and FAO (2015a) all observe that reducing/stabilising deforestation rates have been identified across LAC. The FAO (2015b) observe that rates of forest losses have reduced by more than 50% since 1990, accounted for by improved monitoring, reporting, planning and stakeholder management. However, the identified declines in vulnerability are somewhat inconsistent to the observed, albeit reducing rates of, deforestation (FAO 2015a). A number of factors may have contributed to such differences. The
omission of indicators of vulnerability due to: a lack extensive data (i.e. land tenure), them falling outside of the scope of the analysis (i.e. physical characteristics like slope and aspect), or them not being identified (Vincent 2004) may be accountable. Continual updating of the DVI with new data and indicators when they become available and are identified could help to reduce any potential effects of such omissions. Further, the use of generic weighting for all indicators across all countries may have further contributed. Additionally, these differences may also suggest the existence of a lag between improvements in socio-economic factors and their subsequent benefits in terms of reduced or halted deforestation. Improvements in governance, reductions in population growth or agricultural area growth may not be noted with immediate cessation of deforestation, but take time for the environmental benefits to be realised. The presence of such a lag may be supported by the FAO (2015a), where deforestation rates for the period 2010–2015 were found to have further declined in countries where vulnerability reduced during the period 2000–2010. Further investigation of the presence of such a lag between socio-economic improvements and reduced deforestation could offer an interesting expansion of this analysis.

The DVI does suffer from further limitations, primarily and inherent to most composite indices it analyses countries as uniform. The comparison between Chile with a developed and mature economy and Suriname with a relatively undeveloped and growing economy may be problematic. GDP for example has been identified to have a potential ‘Kuznets’ curve’ effect upon deforestation (Angelsen and Kaimowitz 1999). The DVI considered that higher GDP/capita is beneficial and reduces the vulnerability to deforestation, therefore ignoring its potential bell curve nature. Countries with relatively low GDP/capita were considered to be more vulnerable to deforestation as suggested by the literature (Angelsen and Kaimowitz 1999; Kerr et al. 2004), relative to richer countries.

Despite these limitations, the DVI in its present state offers a simple, yet effective tool for providing easily understood information on spatial and temporal vulnerability trends. The DVI can be used as an aid for policy makers, forest managers, and stakeholders to identify and address the source(s) of forest vulnerability, whilst generating a more refined perspective of forests, facilitating management. Pretzsch et al. (2008) stress the utility of the toolbox approach when it comes to forest management, with diverse and interdisciplinary approaches aiding in decision-making. The DVI can be one such tool, directing reactive and responsive sustainable forest management strategies, tailored to and considerate of the socio-economic vulnerabilities identified by the DVI. Furthermore, the DVI reinforces the inappropriateness of ‘blueprint thinking’ (Ostrom and Cox 2010) when it comes to forest management, demonstrating that sources of vulnerability differ both temporally and spatially. These differences reinforce the need for specific and, where possible, localised management strategies to address vulnerability heterogeneity. The DVI further underscores the benefits of participatory approaches (Wollenberg et al. 2000). The inclusion of stakeholders in the DVI development offered new perspectives and emphasised the differences in opinion concerning the importance of processes driving deforestation, and their considerable effects on DVI outputs. The DVI results and its development demonstrate the benefits of the inclusion of expert and non-expert perspectives. Inclusion of multiple stakeholders could encourage collaborative information-led forest management decision-making (Achyar et al. 2015). Finally, the DVI could also be used in concert with other metrics of forest vulnerability (i.e. Amalina et al. 2016; Mildrexler et al. 2016), to provide a more detailed, better-resolved, multi-faceted and interdisciplinary image of global forests and their vulnerability, further facilitating forest management.
5. Conclusions

The DVI has demonstrated the potential for identifying spatial and temporal patterns of forest vulnerability to deforestation stemming from socio-economic factors and processes. The index has shown small, but widespread reductions in vulnerability across Latin American and Caribbean countries, with heterogeneity in vulnerability seen at various scales of application. The index established that improvements in governance and reductions in the scale of agricultural expansion were responsible for such reductions. The potential existence of a lag between socio-economic improvements, demonstrated by reduced vulnerability, and subsequent reduced deforestation may help to explain why deforestation continues, albeit in declining rates, in countries with reducing vulnerability.

The DVI offers a simple and effective tool for providing easily digested information on spatial-temporal vulnerability trends. It can be used as an aid for identifying the source of forest vulnerability at various scales, whilst directing reactive and responsive sustainable forest management strategies considerate of these socio-economic vulnerabilities. However, there still remains considerable scope for improvement, with greater inclusion of indicators and country specific weighting offering potential for future development, whilst global application could further refine the index and make more concrete global conclusions concerning socio-economic driven forest vulnerability.

Note

1. The complete results of the equal weight analysis are available from the authors upon request.

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