UNIVERSIDAD POLITÉCNICA DE MADRID

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA AGRONÓMICA, ALIMENTARIA
Y DE BIOSISTEMAS

**Drivers, impacts, and policy options to address land use
changes at multiple scales: implications of food
production, rural livelihoods, and ecosystem
conservation**

Tesis Doctoral

Rhys Manners

Master en Cambio Medioambiental Global

Madrid, 2018

Departamento de Economía Agraria, Estadística y Gestión de Empresas
Escuela Técnica Superior de Ingeniería Agronómica, Alimentaria y de Biosistemas
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EL PRESIDENTE

LOS VOCALES

EL SECRETARIO

For my family

Pour y parvenir

No matter how intently one studies the hundred little dramas of the woods and meadows, one can never learn all the salient facts about any one of them.

Aldo Leopold (1966)

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Adfyd a ddwg wybodaeth, a gwybodaeth ddoethineb

Thank you

Diolch

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Abstract

In recent decades the pace, scale, and impacts of land use changes have become unprecedented. In Latin America, forests have reduced by almost 10% since 1990, with an array of drivers and causes implicated in these losses, including global dietary shifts. The scale and speed of deforestation represent considerable challenges for humanity, due to implications for forest based ecosystem services and the development of socio-economic-environmental trade-offs. In light of these changes, this investigation aims to analyse the role of socio-economic, environmental, and institutional factors in Latin American and Caribbean deforestation, explore the historical trends in consumption and production patterns linked to deforestation, and outline strategies to address these changes in the future.

The complexity of studying land use changes, ecosystem conservation, rural livelihoods, and food production suggests the need for a multi-scalar and interdisciplinary methodological approach. This methodology should incorporate and analyse drivers, impacts, and trade-offs, but also allow for the identification of social, political, and economic responses to improve them or ameliorate their impacts. To address this, this investigation develops a composite index to investigate temporal and spatial patterns of forest vulnerability to socio-economic processes in Latin American and Caribbean forests. It applies mathematical goal programming to investigate, at the farm level, the manifestation of these vulnerabilities in the development of ecosystem service trade-offs, and highlights how decision-making may exacerbate these antagonistic relationships. Trend analysis is combined with participatory assessments to elucidate the historical patterns of consumption and production of protein-rich products, identify the barriers and opportunities for plant-protein production and consumption, and develop strategies to increase production and consumption of plant proteins across the European Union. Finally, a crop suitability model is implemented to investigate the potential of protein-rich crops under future European climates.

The findings evidence the benefits of analysing complex processes from distinct perspectives and scales, providing a new understanding and aiding in developing actions to address negative aspects. This thesis has outlined the temporal and spatial differentiation in forest vulnerability to socio-economic factors across Latin America and teased out the sources of recent declines. The results infer the primacy and necessity of stable institutions and governance infrastructures to reduce vulnerability. Farm-scale mathematical goal programming highlighted the antagonistic relationship between maximisation of farm income and protection of ecosystem services, indicating the substantial and overt influence of decision-making on these relationships. These results signal the complex and antagonistic environment within which contemporary policy makers and decision-makers find themselves. They also reaffirm the need for supporting governance infrastructure to assist decision-making.

Continuation of long-term global, continental, and national trends towards greater consumption and production of animal based products were observed, even in wealthier regions like the European Union. Agronomic, supply chain, and consumer awareness barriers were suggested to

be preventing transitions towards plant protein consumption and production. In light of these, four robust strategies were formulated to encourage such transitions: increased research and development, elevated consumer education and awareness, improved and connected supply and value chains, and greater public policy supports. The urgency for the calls for increased research are underlined by the results of the crop modelling analysis. The results demonstrate the divergent effects of climate change upon European agriculture and the potential for novel crops like quinoa as robust protein-rich crop option under future European climates. To exploit the potential of protein-rich crops as potential animal product replacements in European agricultural systems, geographically differentiated planning, research, and breeding strategies should be implemented.

The results of this investigation offer a series of outputs that can contribute to improving the knowledge base of the interactions between land use changes, ecosystem conservation, rural livelihoods, and food production to better inform future decision-making. In particular, to improve sustainable management of forests, reduce the extent of trade-offs in agriculture-forest systems, outline options for reducing external socio-economic pressures upon forests, and derive potential policy options for achieving the aforementioned. This research has established the benefits of a novel methodological approach for analysing land-use changes and for parsing out the interactions between them and socio-economic processes. The selection and combination of previously applied methodologies in an innovative manner has provided an enhanced understanding of food production, rural livelihoods, and ecosystem conservation at multiple scales.

Resumen

En las últimas décadas, el ritmo, la escala y los impactos de los cambios en el uso del suelo no tienen precedentes. En América Latina, la superficie de bosque ha disminuido en torno al 10% desde 1990 como consecuencia de diversas causas, entre las que se incluyen los cambios en la dieta hacia un mayor consumo de productos animales a nivel global. La escala y la velocidad de la deforestación y la degradación de los bosques representan un desafío considerable para la humanidad, sobre todo debido a las implicaciones e impactos sobre los servicios de los ecosistemas forestales y los consiguientes trade-offs socio-económico-ambientales. A la luz de estos cambios, esta investigación tiene como objetivo analizar el papel de los factores socioeconómicos, ambientales e institucionales en la deforestación de América Latina y el Caribe, al tiempo que investiga las tendencias históricas en los patrones de consumo y producción vinculados a la deforestación y propone estrategias para aliviar presiones ambientales derivadas de los cambios en la dieta en la Unión Europea.

La complejidad de estudiar los cambios en el uso del suelo, la conservación del ecosistema, los medios de vida rurales y la producción de alimentos requiere la aplicación de un enfoque metodológico multiescalar e interdisciplinario. Esta metodología debe incorporar y analizar los factores impulsores, los impactos y las compensaciones, pero también permitir la identificación de respuestas sociales, políticas y económicas. Para abordar esto, esta investigación se desarrolla un índice compuesto para analizar los patrones de vulnerabilidad temporal y espacial derivados de los procesos socioeconómicos en los bosques de América Latina. Estrechando el foco en cuestiones más localizadas, se desarrolla un modelo a nivel de explotación utilizando programación matemática multi-objetivo para estudiar la manifestación de estas vulnerabilidades y el desarrollo de trade-offs de los servicios ecosistémicos, mientras se destaca cómo la toma de decisiones puede exacerbar las relaciones antagónicas. Además, el análisis de tendencias se combina con evaluaciones participativas para dilucidar los patrones históricos de consumo y producción de productos ricos en proteínas, analizar las barreras y oportunidades para el cambio hacia dietas sostenibles y desarrollar estrategias para la producción y el consumo sostenible de proteínas en toda la Unión Europea. Finalmente, se implementa un modelo de idoneidad del cultivo para investigar el potencial de la transición de las actividades de producción hacia modelos más sostenibles, para aliviar las presiones sobre los bosques en climas futuros.

Los resultados de esta investigación evidencian los beneficios de analizar procesos complejos desde distintas perspectivas y a diferentes escalas, proporcionando una nueva comprensión de su complejidad, a la vez que ayudan a desarrollar acciones para abordar los aspectos negativos. Esta tesis demuestra la diferenciación temporal y espacial de la vulnerabilidad de los bosques a los factores socioeconómicos en América Latina, al tiempo que revela las causas de las disminuciones recientes en la vulnerabilidad a escala nacional. Los resultados revelan la primacía y la necesidad de instituciones estables e estructuras de gobernanza para alentar la disminución de la vulnerabilidad. La programación matemática multi-objetivo al nivel de explotación demostró la relación antagónica entre la maximización de los ingresos agrícolas y la protección de los servicios ecosistémicos como el secuestro de carbono, al tiempo que indicaba la influencia

sustancial y manifiesta de la toma de decisiones sobre estas relaciones. Estos resultados señalan el entorno complejo y antagónico en el que se encuentran los responsables políticos y los tomadores de decisiones contemporáneos y reafirman la necesidad de apoyar la infraestructura de gobernanza para ayudar a la toma de decisiones sostenibles.

Esta investigación demuestra la continuación de las tendencias mundiales, continentales y nacionales hacia un mayor consumo y producción de productos de origen animal. Las supuestas transiciones hacia sistemas alimentarios más sostenibles (mayor consumo y producción de productos vegetales en lugar de productos animales) no se observaron ni siquiera en las regiones más ricas como la Unión Europea. Barreras agronómicas, de la cadena de suministro y de la conciencia del consumidor pueden evitar tales transiciones. A la luz de estos, grupos de interés se formularon cuatro estrategias robustas para fomentar tales transiciones: investigación y desarrollo; educación y conciencia del consumidor; cadenas de suministro y valor mejoradas y conectadas y apoyo de políticas públicas. Los resultados del análisis del modelo de cultivos revelan la urgencia de la necesidad de una mayor inversión en investigación. Los resultados muestran efectos divergentes del cambio climático sobre la agricultura europea y evidencia el potencial para la producción de cultivos novedosos, como la quínoa, como opciones robustas de cultivos ricos en proteínas en climas futuros. Para aprovechar el potencial de los cultivos ricos en proteínas como sustitutos de productos animales en los sistemas agrícolas europeos, se deben implementar estrategias de planificación, investigación y mejora geográficamente diferenciadas.

Los resultados de esta investigación contribuyen a mejorar la base de conocimiento de las interacciones entre los cambios en el uso del suelo, la conservación del ecosistema, los medios de vida rurales y la producción de alimentos para apoyar la toma de decisiones en el futuro. En particular, aquellas vinculadas a la mejora de la gestión sostenible de los bosques, la reducción del alcance de las compensaciones en los sistemas agrícolas y forestales, el desarrollo opciones que permitan reducir las presiones socioeconómicas externas sobre los bosques y, en definitiva, el diseño de posibles opciones políticas para lograr lo mencionado. Esta investigación demuestra los beneficios de la aplicación de un nuevo enfoque metodológico para analizar los cambios en el uso del suelo y analizar las interacciones entre ellos y los procesos socioeconómicos. La selección de metodologías aplicadas previamente y su combinación de una manera innovadora, por lo tanto, ha proporcionado una mejor comprensión de la producción de alimentos, los medios de vida rurales y la conservación del ecosistema en múltiples escalas.

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LIST OF ABBREVIATIONS

ABT	Autoridad de Fiscalización y Control Social de Bosques y Tierra, Bolivia
CCAFS	Climate Change, Agriculture and Food Security
CES	Conservation of Ecosystem Services
CIAT	Centro Internacional de Agricultura Tropical
CONAFOR	Comisión Nacional Forestal, Mexico
CS	Carbon Sequestration
DM	Decision-maker
DSC	Department of Santa Cruz
DVI	Deforestation Vulnerability Index
ES	Ecosystem Services
EU	European Union
FAO	Food and Agricultural Organization
FAPESPA	Fundação Amazônia de Amparo a Estudos e Pesquisas
FBS	Food Balance Sheets
FCM	Fuzzy Cognitive Mapping
FT	Forest Transition
GCM	Global Circulation Model
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GP	Goal Programming
ha	Hectare
HDI	Human Development Index
IBGE	Instituto Brasileiro de Geografia y Estadística, Brazil
INE	Instituto Nacional de Estadística, Bolivia
INEGI	Instituto Nacional de Estadística y Geografía, Mexico
INPE	Instituto Nacional de Pesquisas Espaciais, Brazil
IPCC	Intergovernmental Panel on Climate Change
ISRIC	International Soil Reference and Information Centre
LAC	Latin America and Caribbean
LULCC	Land Use Change and Land Cover Change
MEA	Millennium Ecosystem Assessment
Mha	Million Hectares
MOGP	Multi-Objective Goal Programming
MS	Member State (European Union)
MT	Million Tonnes
NUTS	Nomenclature of Territorial Units for Statistics
OECD	Organisation for Economic Co-operation and Development
PMP	Positive Mathematical Programming
POG	Province of Guarayos
PPP	Price Purchasing Parity
PROTEIN2FOOD	Development of high quality food protein from multi-purpose crops through optimized, sustainable production and processing methods
RCP	Representative Concentration Pathways, EU Project
ROBIN	Role Of Biodiversity In climate change mitigation, EU Project
SED	Socio-Economic Development
SIAP	Servicio de Información Agroalimentaria y Pesquera, Mexico
SOC	Soil Organic Carbon

SOJ	State of Jalisco
TEEB	The Economics of Ecosystems & Biodiversity
UNDP	United Nations Development Programme
UPM	Universidad Politécnica de Madrid
USD	United States Dollar
USDA	United States Department of Agriculture
yr	Year

1. INTRODUCTION

1.1 Research Context

This PhD thesis is based upon studies performed from 2014-2018 within the Department of Agricultural Economics, Statistics, and Business Management of the School of Agricultural, Food and Biosystems Engineering at the Universidad Politécnica de Madrid (UPM). This research received funding from UPM via their contracts for pre-doctoral researchers (*Contractors Predoctorales en el Marco del Programa Propio de Ayudas para el Personal Investigador en Formación*) during the period 2016-2018.

This work was developed, structured, and further funded (2014-2016) by two European Commission projects. In both cases, Professor Consuelo Varela-Ortega coordinated the UPM team. These projects were:

- **ROBIN** (The Role Of Biodiversity In climate change mitigationN). Project No. 283093. 7th Framework Programme. EU Commission, 2011-2015.
- **PROTEIN2FOOD** (Development of high quality food protein from multi-purpose crops through optimized, sustainable production and processing methods). Project No. 635727-2. Horizon 2020 Programme. EU Commission, 2015-2020.

The aims of ROBIN (www.robinproject.info) were to: 1) quantify the role of biodiversity in mitigating climate change in Latin and Meso-American ecosystems; 2) quantify the interactions from local to regional scales between biodiversity, land use, and the potential for climate change mitigation. Within ROBIN, three case study sites were developed: Province of Guarayos (Bolivia); Tapajós National Forest (Brazil) and the Cuitzmala river basin (Mexico). Within the framework of the project, specific field-work activities and stakeholder interactions were performed in two case studies: the Province of Guarayos and the Tapajós National Forest. ROBIN provided foundations to the thesis structuring and knowledge development of two of its component themes: land-use changes and ecosystem service trade-offs at multiple scales.

PROTEIN2FOOD (www.protein2food.eu) aims to develop innovative, cost-effective, and resource-efficient food crops that are high in protein, with a positive impact on human health, the environment and biodiversity. This project is largely concentrated upon the production and consumption of plant proteins within Europe, specifically EU-28 countries. The work developed within the framework of PROTEIN2FOOD applied methodologies to highlight the changes in consumption and production patterns at multiple scales, whilst suggesting potential strategies to transition these patterns towards more sustainable futures.

To further develop and complement the research carried out at UPM, as part of these European projects, a research stay was completed at Bioversity International, Costa Rica. The three-month

stay (September 15th- December 15th, 2017) was performed under the supervision of Dr Jacob van Etten and funded by a UPM grant (*Ayudas a los beneficiarios de los programas predoctorales oficiales de formación de investigadores para estancias breves en el extranjero*). The research stay was used to refine and develop a methodology for analysing the potential of protein-rich crops, often cited as potential replacements for animal based products, under future climates to assist in future decision-making.

1.2 Related Publications

Through the implementation of this investigation a series of publications were developed which include research articles, presentations in international congresses, and seminars.

Publications

Manners, R. and Varela-Ortega, C. (2018) The role of decision-making in ecosystem service trade-offs in lowland Bolivia's Amazonian agricultural systems. *Ecological Economics*. 153:31-42. Doi:10.1016/j.ecolecon.2018.06.021.

Manners, R. and Varela-Ortega, C. (2017) Analysing Latin American and Caribbean forest vulnerability from socio-economic factors. *Journal of Integrative Environmental Sciences*. 14:109-130. Doi:10.1080/1943815X.2017.1400981

Manners, R. Varela-Ortega, C. and van Etten, J. Protein-rich legume and pseudo-cereal crop suitability under present and future European climates. *European Journal of Agronomy*. (Under Review: EURAGR_2018_50)

Manners, R., Varela-Ortega, C., Blanco, I. and Esteve, P. Developing robust strategies and policy suggestions for transitioning European protein-rich food consumption and production towards more sustainable patterns. *Food Policy* (Under Review: FOODPOLICY_2018_527)

Congresses

Manners, R. and Varela-Ortega, C. Analysing vulnerability to deforestation of Latin American and Caribbean forests. European Geophysical Union General Assembly. Vienna, Austria. 14th May 2015.

Varela-Ortega, C., Esteve, P., Manners, R., Blanco-Gutiérrez, I. and Barrios, L. Analysis of current patterns of deforestation in Latin America and the Caribbean. European Society for Ecological Economics 2015: Transformations. University of Leeds, UK. 1st July 2015.

Blanco, I., Varela-Ortega, C., Manners, R., Esteve, P., Martorano, L. and Toledo, M. Understanding environmental change through the eyes of locals: a comparative analysis in

tropical rainforest agro-ecosystems in Bolivia and Brazil. XI Congreso Iberoamericano de Estudios Rurales. Segovia, Spain. 4th July 2018.

Seminars

Manners, R. and Varela-Ortega, C. Analysing Latin American and Caribbean forest vulnerability: an alternative approach using a composite index. CEIGRAM, Universidad Politécnica de Madrid. 22nd May 2015.

Manners, R. Agricultural expansion as a driver of change- A multi-scale analysis in Latin America. IRI-THEsys, Humboldt University, Germany. 27th September 2016.

Varela-Ortega, C., Blanco, I., Manners, R., Sango-Lucas, S. and Esteve, P. WP4 Market Analysis. Protein2Food annual meeting. Freising-Munich, Germany. 1st March 2018

1.3 Historic and Contemporary Land Use Changes

In recent centuries and in particular recent decades the pace, scale, and impacts of Land Use Change and Land Cover Change (LULCC) have become unprecedented (Lambin et al., 2001). LULCC are changes in biophysical attributes and modifications in the purpose of these attributes (Lambin et al., 2001). The forces behind these transformations can be natural (e.g. drought, fire, and disease) or anthropogenic (for habitation, farming, and resource collection). As methods of anthropogenic driven changes have evolved (from localised slash and burn to industrial landscape-scale alterations), so have their impacts. Contemporary land use changes are so pervasive and have escalated to such an extent that they are implicated in driving epoch-defining extinction rates (Crutzen and Stoermer, 2000; Ceballos et al., 2017), indirectly threatening systems on which humanity depends (Lobell et al., 2011; Challinor et al., 2014), and the stability of planetary systems (Houghton et al., 2012; Baccini et al., 2017).

Global forests have been subject to anthropogenic driven transformations for millennia, used as sources of fuel, building materials, and food (Hughes and Thirgood, 1982; Willis et al., 2004; Kaplan et al., 2012). Forests have cycled through periods of deforestation¹ and reforestation, as the interventions and intensity of human activities have cycled (Mbida et al., 2000; Berrios et al., 2002; Willis et al., 2004). Goldewijk and Ramankutty (2001) estimate that global forests declined by up to 25% from 1700 to 2000. In contrast, croplands and pastures simultaneously increased by 550% and 660% respectively (Goldewijk, 2001). The pace and scale of modern deforestation far outstrips pre-industrial and more contemporaneous rates. As of 2015, global forests covered just over 30% of global land area, totalling 4000 million hectares (Mha), declining between 3-6% since 1990 (FAO, 2015b; Keenan et al., 2015). The extent and distribution of such losses (for the period 2000-2012) are presented in Figure 1. Despite these losses, net annual global deforestation rates are slowly reducing (FAO, 2015b).

However, aggregated global figures mask the spatial diversity of forest losses. Tropical and subtropical areas saw forest coverage reduce by 9% to 2090 Mha, contrasting with temperate forest area, which increased by 10% to 680 Mha (Keenan et al., 2015). The majority of these tropical losses occurred in Latin American and Caribbean (LAC) countries, which saw reductions of 9.3 Mha (9.7%) from 1990-2014 (FAO, 2015b) (Annex 1: LAC forest area and forest area changes from 1990-2014). Figure 1 highlights that Latin America, particularly the Amazon basin, is a hotspot of global forest losses (as highlighted in red).

¹ The FAO (2015a) define deforestation as “The conversion of forest to other land use or the permanent reduction of the tree canopy cover below the minimum 10 percent threshold”.

Figure 1. Global tree cover extent, loss, and gain for the period 2000- 2012.

Source: Hansen et al. (2013)

1.4 Impacts of Deforestation

The scale and speed of deforestation and forest degradation represent considerable challenges. Not least due to the implications and impacts upon forest based ecosystem services (ES). Global forests are estimated to sequester up to 1400 (± 400) Tg of carbon per year, providing important regulating services for the global climate (Schimel et al., 2015). In contrast, emissions from LULCC are estimated between 810-1140 Tg C yr⁻¹ (Baccini et al., 2012; Harris et al., 2012; Houghton et al., 2012). Recent studies now propose that tropical forests, rather than being net carbon sinks, may in fact be net carbon sources (Baccini et al., 2017). Baccini et al. (2017) suggest that emissions from deforestation and reductions in forest carbon density due to degradation, may be as high as 861.7 $\pm$ 80.2 Tg C yr⁻¹. These emissions contribute to climate change and may subsequently limit the integrity and resilience of globally important regions such as the Amazon basin (Giles, 2006; Brando et al., 2008; Spracklen and Garcia-Carreras, 2015). Lenton (2011) suggests that forest conservation is fundamental for limiting global temperature increases beyond 2°C. Baccini et al. (2017) found that reducing deforestation and forest degradation to zero could offer a pathway for reducing global emissions by 862 Tg C yr⁻¹, equivalent to 1.8% of annual global GHG emissions (IPCC, 2014).

A further product of deforestation in LAC countries is its impacts on biodiversity (Achard et al., 2002; Rosa et al., 2016). Deforestation driven biodiversity losses are acute in highly biodiverse LAC forest systems (Mittermeier et al., 2003; Peres et al., 2010). An estimated 28 vertebrate species have recently disappeared in the Amazon alone (Rosa et al., 2016), with greater future losses expected (Rosa et al., 2016). Liang et al. (2016) suggest that further forest species losses could have detrimental effects upon global carbon sequestration sinks, coinciding with Baccini et al. (2017). Deforestation is also associated with profound changes to soil quality (Grimaldi et al., 2014), with soil organic carbon (SOC) levels in deforested tropical forests found to reduce (Fujisaki et al., 2017). Lal (2006) suggest that these changes can be linked to reduced crop production. Coupled to this, Oliveira et al. (2013) found that deforestation may further impact agricultural output and productivity, concluding that replacement of forests with agricultural activities may drive a vicious cycle, where more agricultural expansion may reduce productivity due to precipitation changes. The indirect impacts upon agriculture may already be notable, with farms growing increasingly larger in order to support incomes, due to ecosystem service degradation along a deforestation succession continuum (Lavelle et al., 2016). Despite these observations, Raudsepp-Hearne et al. (2010) conclude that the social benefits of deforestation gained via increased food production, outweigh the costs to other ecosystem services, at the global scale. At more localised scales, Barbier et al. (2008) found that the impacts from ecosystem services losses due to agricultural activities can be extensive.

Destruction of natural capital (e.g. deforestation) and human appropriation of ecosystem services may be driving an environmental debt, that may not currently have widespread socio-economic impacts globally, but progressively impacts are predicted to be large (Lal, 2006; Foley et al., 2007; Rodrigues et al., 2009). This debt could manifest itself environmentally, through soil

degradation and reduced water quality affecting agricultural activities (Raudsepp-Hearne et al., 2010), but also could have social impacts through the effects of ES losses on human wellbeing (e.g. Sandifer et al., 2015). ES losses have been linked to increased stress (Fritze et al., 2008), declining life satisfaction (Carroll et al., 2009), and increased anxiety (Satore et al., 2008). Social impacts of ES losses directly associated with agricultural activities have been implicated in increased financial pressures, population declines, and reduced employment opportunities due to reduced productivity and land values (e.g. Staniford et al., 2009; Caldwell and Boyd, 2009).

1.5 Drivers and Causes of Deforestation

Deforestation events are highly site-specific, but may follow predictable temporal and spatial patterns (Mather, 1992; Angelsen, 2007). The Forest Transition (FT) theory (Mather, 1992) suggests that forests follow predictable temporal patterns, concomitant to economic development, agricultural expansion, urbanisation, and industrialisation (abridged in Figure 2). Forest area initially reduces as demand for land increases with growth in population and economic activities (such as agriculture), before a developmental inflection point is reached, with forest area slowly rising again (Köthke et al., 2013).

Figure 2. The forest transition curve.

Source: Köthke et al. (2013)

The von Thünen model (von Thünen, 1826) and more contemporary interpretations (e.g. Angelsen, 2007) describe spatial patterns of deforestation, based upon the assumption that land rents determine land use. Temporal changes in agricultural rents due to high prices, population, increased demand, suitable agricultural conditions, technological improvements, access to

credit and infrastructure development are posited to increase deforestation rates, before reductions or stabilisation in rents reduce deforestation and eventually reforestation (Angelsen, 2007). Although the processes behind these suggested patterns of deforestation can be highly specific, the general forces of deforestation were elegantly presented in the seminal paper by Geist and Lambin (2002) as proximate causes and underlying drivers.

Proximate causes are direct human activities such as agricultural expansion (Aide et al., 2013), expansion of infrastructure (Hosunuma et al., 2012), and wood extraction (Echeverria et al., 2008). These causes are in many cases intertwined and mutually dependent, with agricultural expansion coinciding with infrastructure expansion. This expansion is driven by demands for resources including arable land and timber, with timber extraction being the result of both agricultural expansion and infrastructure development (Laurance et al., 2014). The impacts of these causes are not limited to deforestation, but also extend to biodiversity loss, land-use conflicts, aquatic system functionality, and climate change (Asner et al., 2009; Michalski and Peres, 2013; Laurance et al., 2014; Machovina and Feeley, 2014; Baccini et al., 2017).

The underlying drivers behind these causes are highly diverse, site-specific social processes (Geist and Lambin, 2002). In many cases it is not a single driver, but a series of often self-reinforcing processes, which create the socio-economic conditions that drive deforestation events. Demographic conditions are one of the most widely recognised of these processes; population growth, immigration, and population densities are widely associated with deforestation (Goldewijk, 2001; Scrieciu, 2007; Huang et al., 2007; Bonilla-Moheno et al., 2012). The role of poor governance has also been observed to encourage conditions for resource extraction and deforestation (Fearnside, 2006). Ineffective governance can drive land tenure insecurity, with farmers using land clearing and deforestation as a means of establishing land titles in conditions of insecurity (Angelsen and Kaimowitz, 1999; Müller et al., 2014). The benefits of strong governance and democratic institutions for balancing natural resource conservation with socio-economic development are well explored (Didia, 1997; Nepstad et al., 2014; Wehkamp et al., 2018).

The role of infrastructure in deforestation is complex, not only being a cause, but also a driver (Müller et al., 2012). Further, improvements and expansion in infrastructure can also permit access to more efficient agricultural technology and methods, which have also been described as a driver of deforestation (Gasparri and Grau, 2009).

Economic factors and economic development are recognised and fundamental to the aforementioned spatial (Angelsen, 2007) and temporal (Köthke et al., 2013) patterns of deforestation. Economic development is often documented as a precursor to deforestation, with increased wealth increasing resource use and lifestyle improvements, driving greater utilisation of resources and need for land to further support and continue these patterns. However, economic factors as drivers are not concrete, but can be fluid, with per capita affluence suggested to both encourage and suppress deforestation, stimulating demand at the

individual level, whilst improving conservation efforts at the government level (Angelsen and Kaimowitz, 1999) as modelled by the FT. In recent years and within an increasingly globalised and interconnected economy, a particularly important affluence based driver of deforestation has manifested itself in dietary changes, with increasingly wealthier individuals consuming more resource intensive products, like animal products (Godfray et al., 2010; Kastner et al., 2012; de Ruiter et al., 2014).

1.6 Forest Vulnerability and Landscape-Scale Trade-Offs

The wealth of studies dedicated to the drivers and causes of deforestation highlight not only their diversity, multi-scalar nature, but also in many cases the increments in their intensity. The identification of these factors and their associated effects upon forest area are suggestive of forest vulnerability to their presence. Using a positivist slant, Turner et al. (2003) defines vulnerability as the harm experienced from exposure to a hazard(s). If such a definition is applied to forest ecosystems, then their exposure to the aforementioned drivers and causes, implies their vulnerability from continued exposure.

Previous analyses of forest vulnerability although diverse, invariably concentrated upon, with good reason, climatic conditions and fire (e.g. Allen et al., 2015; Nurdina and Risdiyanto, 2015; Amalina et al., 2016; Mildrexler et al., 2016). These analyses indirectly studied vulnerability to socio-economic development, through the guise of anthropogenic driven climate change induced drought, or fire hazards. However, limited analysis has been dedicated to the explicit relationship between socio-economic dynamics and forest vulnerability. Although examples can be found where socio-economic factors have been integrated within vulnerability analyses (e.g. Chuvieco et al., 2014; Vogt et al., 2016), analyses of direct vulnerability of forests to socio-economic factors are limited. Vilar et al. (2014) addressed the explicit link between socio-economic factors and anthropogenic driven forest fires. They highlighted the heterogeneity of vulnerability at multiple scales and the significant vulnerability of forests to certain socio-economic factors. These findings suggest the potential for quantifying direct links between forest vulnerability and socio-economic processes. Such quantification could offer a better resolved and more accurate interpretation of the state of contemporary forests, strengthening and diversifying the toolbox for forest management (Pretzsch et al., 2008).

As outlined, the increments in causes and drivers of deforestation have likely driven the contemporary state of modern LAC forests, where the scale and speed of deforestation and forest degradation represents a considerable challenge for humanity, due to the implications and impacts upon the ES that forests provide. These services are manifold and are fundamental to global systems (Malhi et al., 2008; Aragão, 2012). However, the scale of forest losses may undermine the capacity of forests to sustain these services at current levels (Nepstad et al., 2008; Oliveira et al., 2013; Lapola et al., 2014). In particular, forests' capacity for climate regulation (Saatchi et al., 2011; Harris et al., 2012; Baccini et al., 2017) and habitat integrity (Haddad et al., 2015) is now being questioned. Agricultural activities, as a product of socio-

economic processes and development, are now implicit contributors to multi-scale trade-offs of ecosystem service provision, and are complicit in threatening global systems. Lavelle et al. (2016) elegantly display the progressive nature of these trade-offs, with human well-being, agricultural production, and income indices rising as biodiversity and regulating ecosystem services decline along the succession from intact forest to agricultural landscapes.

Although the environmental impacts of deforestation are, as demonstrated, large and wide-ranging, the provisioning of food, fuel, building materials, employment, and incomes from these activities (Foley et al., 2007) are important for rural development (DeFries et al., 2004). The positive social impacts, or benefits, of deforestation are understood, with human development improvements coming at the cost of natural capital losses. Newton et al. (2013) suggest that agricultural expansion in forest regions also represents a wider conflict between development and conservation, with forests conserved for their wider societal benefits (Gibson et al., 2011), and agricultural areas expanding to stimulate rural economic development (Diversi, 2014). The Millennium Ecosystem Assessment found that over the 50 years analysed, human well-being improved concomitantly with the destruction and conversion of natural landscapes (Millennium Ecosystem Assessment [MEA], 2005). This observation is further supported by Rodrigues et al. (2009) who found that human development improves during the early stages of land use change and deforestation. Lavelle et al. (2016) observed that conversion of forests to agricultural activities can also be associated in some cases with improved social well-being due to reduced isolation, improved health care and education, and connection to infrastructure.

The trade-offs between environmental integrity and socio-economic development present particular issues for land-use planning (Goldstein et al., 2012). Braat and de Groot (2012) propose the need to identify balances between multiple ES to improve land-use management. Balvanera et al. (2012) suggest that analysis of management strategies in ES relationships can facilitate decision-making and policy development. It could also assist in reducing conflicts and identifying efficient management solutions (Viglizzo et al., 2006; Power, 2010; White et al., 2012). Lavelle et al. (2016) offer that analysis and subsequent optimisation of these trade-offs could offer a sustainable route forward in highly conflict-ridden regions and improve land-use efficiency (Godar et al., 2014).

Although analysis of these relationships is important, it should not negate the importance of stakeholder preference and decision-making in driving their development. Understanding the role of decision-making in these dynamic situations and the subsequent impacts upon ES is imperative (Nelson et al., 2008). To develop sustainable solutions to antagonistic situations, recognition and analysis of divergent preferences of stakeholders, or decision-makers, within a system is necessary (King et al., 2015; Cavender-Bares et al., 2015). Consideration of the inherent role of decision-making in ES relationships is therefore important for future policy making and land-use planning (Goldstein et al., 2012). Investigating ES relationships and decision-making may avoid undermining the long-term provision of certain ES through unsustainable exploitation (Raudsepp-Hearne et al., 2010; Dearing et al., 2012).

1.7 Dietary Change as a Global Driver of Change

An array of studies has highlighted how global dietary changes have contributed to increasingly degraded and conflict-ridden systems (Godfray et al., 2010; Foley et al., 2011; Aide et al., 2013; Machovina et al., 2015). Agriculture accounts for up to 35% of anthropogenic greenhouse gas emissions (Foley et al., 2011; Vermeulen et al., 2012), 80% of which is associated with livestock rearing (Tubiello et al., 2013). Dietary changes are now so acute that animal production dominates global agricultural land-use, occupying (directly or indirectly) at least 75% of agricultural land (Steinfeld et al., 2006; Alexander et al., 2015; Ranganathan et al., 2016).

These figures are the manifestation of socio-economic driven shifts in global diets (Kastner et al., 2012). Larger, wealthier, and increasingly urban populations have shifted from cheaper plant-based foods, to costlier diets rich in animal products (Vranken et al., 2014). Popkin (1997) identified the link between socio-economic development and consumption transitions towards animal based products. Delgado (2003) demonstrated the acuteness of these changes in developing regions. More recently, Sans and Combris (2015) found that global consumption of animal products has increased by almost 30% since 1961, with animal proteins accounting for 37-40% of dietary protein (Boland et al., 2013; Poore and Nemecek, 2018). In wealthier regions, this figure is even greater, with de Boer et al. (2006) and Bonhommeau et al. (2013) observing that animal proteins supply the majority of dietary protein in contemporary European and North American diets. These shifts are so great that average global protein consumption now exceeds recommended allowances (Ranganathan et al., 2016). Machinova and Feeley (2014) describe these trends as one the greatest threats to biodiversity and tropical ecosystems, a conclusion echoed by Tilman and Clark (2014).

Expansion in arable land and pastures (Figure 3a and b) to supply feed crops for livestock have been identified to come at the expense of native forests in LAC countries (Steinfeld et al., 2006; McAlpine et al., 2010; Aide et al., 2013). The scale of these expansions across LAC countries is evident in Annex 2 (LAC arable area and arable area changes from 1990-2014) and Annex 3 (LAC grassland area and grassland area changes from 1990-2014). The production of soya in LAC has been key to satisfying the burgeoning global market for animal products (Aide et al., 2013). Figure 3a evidences the extent of these changes highlighting the soya area harvested in LAC to supply the demands of global pork and poultry production which has more than doubled since 1990. Pastures have increased across LAC (Figure 3b) to support the growing LAC cattle stocks.

Figure 3. Land-use change and export products relationship in South America.

Note: A) Global pig and poultry production and soybean production in South America. B) Permanent pastures in South America and mean bovine exports.

Source: Updated from Aide et al. (2013) using FAO data (FAO, 2018a).

In the 15 years from 2000-2015, total soya exports from the most important LAC producers (Brazil, Argentina, Bolivia, Paraguay, and Uruguay) increased by more than 350% (20-72 million tonnes) (UN Comtrade, 2017). Furthermore, a geographical shift in importing regions reflects the global-scale and geographical shift (associated with economic development) of these dietary changes. In 2015, more than 80% of exports were sent to Asia, compared to 32% in 2000. In Europe, soya imports from LAC producers remained relatively stable (UN Comtrade, 2017). Despite this, European livestock feed-stuffs are largely imported, with imported soybean accounting for 97% of soybean supply (de Visser et al., 2014). These imports have now largely replaced domestic production of protein-rich feed-stuffs, in particular legumes (Zander et al., 2017). The environmental impacts of these imports are sizable, with de Visser et al. (2014) estimating that European soya imports are equivalent to roughly 13 Mha of arable land outside of Europe.

Continued expansion of diets rich in animal products are widely expected (Bailey et al, 2014; Tilman and Clark, 2014; Ranganathan et al., 2016), even in wealthier regions like the European Union (Bodirsky et al., 2015; Ranganathan et al., 2016). The long-term consequences of maintenance of these changes have led to suggestions that without future targeted dietary changes, the associated environmental and health impacts will be grave (e.g. Springmann et al., 2016; Etemadi et al., 2017), especially considering global population growth (Tilman et al., 2011). The United Nations Environment Programme (UNEP, 2010) conclude that reduction of the environmental impacts from agriculture can only be achieved through substantial dietary changes.

The benefits of reversing current and projected future trends in animal product consumption and stimulating future consumption transitions less reliant upon animal products for dietary protein have been widely espoused from environmental (Cassidy et al., 2013; West et al., 2014; Tilman and Clark, 2014; Schader et al., 2015; Erb et al., 2016), human health (Larsson and Wolk,

2006; Tilman and Clark, 2014; Bouvard et al., 2015; Springmann et al., 2016), and financial perspectives (Springmann et al., 2016). Targeted changes to reduce meat consumption could cut dietary based emissions between 29-70% (Springmann et al., 2016), supply adequate dietary calories to over 10 billion people (Cassidy et al., 2013), avert 5-8 million health related avoidable deaths (Springmann et al., 2016), and reduce deforestation driven by agricultural activities to zero (Erb et al., 2016).

Adoption of the 'Mediterranean' (Tilman and Clark, 2014), vegetarian or vegan diets (Cassidy et al., 2013; Erb et al., 2016) high in plant products and proteins from cereals or legumes (Hedenus et al., 2014), or diets with reduced total protein consumption (Ranganathan et al., 2016) have been proposed as beneficial consumption end-points. Henchion et al. (2017) and Harwatt et al., (2017) evidence the potential of legumes in these changes, due to their high protein content (United States Department of Agriculture [USDA], 2017), nutrient density (USDA, 2017), general health benefits (Delgado-Andrade et al., 2016; Clemente and Olias, 2017), limited environmental impacts (Springmann et al., 2017; Poore and Nemecek, 2018), and agronomic benefits (Watson et al., 2017). Legumes are in many cases more nutrient dense, with comparable protein contents, compared to protein rich cereals (e.g. wheat) (USDA, 2017), which can be a more common source of plant based dietary protein (Food and Agricultural Organization [FAO], 2016a). Despite these benefits, legume cultivation is limited across much of the world, the EU in particular has seen long-term production declines over recent decades (Magrini, et al. 2016). A series of agronomic (unstable yields), social (low demand), and economic (path dependency) factors have been implicated in these declines (Voison et al. 2014; Reckling et al. 2015, Magrini et al., 2016). de Boer et al. (2006) suggest that consumption of these products has also seen widespread declines across the EU.

Notwithstanding observed increases in the levels of vegetarianism in developed countries (Beverland, 2014) and the renewed importance that consumers attach to health and ethical factors in their diets (Wirsenius et al., 2010), consumer perceptions of future dietary trends suggest that shifts to vegetarianism and veganism are distant and unlikely (Judge and Wilson, 2015). Further, demand for protein-rich legumes is projected to decline across the European Union (Bodirsky, personal communication). Therefore, dramatic shifts in consumer attitudes would be required to achieve advocated consumption changes (Wirsenius et al., 2010; Ritchie et al., 2018). These observations evidence a divergence between two modelled futures: an idealised future landscape, where environmental and health impacts of animal product consumption and production are reduced, or eliminated; versus a projected future landscape, where current trends in consumption and production continue.

Idealised future conditions (e.g. Cassidy et al., 2013; Springmann et al., 2016) characterise significant cultural and agronomic systemic changes with wide-spread vegetarianism and veganism. The beneficial impacts of these changes are often presented and discussed in the narrow terms of mechanisms for their achievement (e.g. taxation of animal products) and the subsequent effects (e.g. reduced dietary based emissions). However, characterisation of

strategies and policy requirements to encourage such cultural and agronomic changes described in these idealised futures are often omitted. This is not a criticism of such approaches, the utility of which are unquestionable for framing the argument for the need of dietary changes and presenting potential future conditions. These omissions do however make it necessary to begin to define strategies and required policy options to encourage a shift from the present, to an idealised future.

However, in modelling futures and considering options of moving towards more desirable futures, it is prudent not to consider production and consumption patterns in a vacuum. Considerations need also be made of other future global changes. As agriculture is one of the economic sectors most exposed to climate change (Hansen, 2002), any analysis of future production activities should also be considerate of climate change and its potential impacts. Estimated global temperature increases between 1.5°-4.9°C by 2100 (Intergovernmental Panel on Climate Change [IPCC], 2014; Raftery et al., 2017) are likely to have profound effects upon crop distribution (Chaves et al., 2003), production and productivity (Delgado et al. 2011), and farm-scale decision-making (Jones and Thornton, 2008). Consideration of these observations should therefore be included in any future analysis of production activities, and identifying potential protein-rich crops to replace animal products.

Both Tol et al. (2004) and Lobell et al. (2011) observe notable impacts of climate change in global agricultural activities, with future changes widely expected (Challinor et al., 2014). Large-scale analyses of climate change impacts however have largely concentrated upon major crops (maize, wheat, soya, and rice) for which well-developed crop growth models are available (e.g. Rosenzweig et al., 2014; Challinor et al., 2014). Despite the observed and modelled impacts, little research attention has been paid to the potential impacts of climate change on minor crops, like protein-rich legumes. Analyses for these crops (excluding soya) are limited, with exceptions (e.g. Basu et al., 2016; Ramirez-Cabral et al., 2016; Mohammed et al., 2017). Unfortunately, such analyses are almost non-existent across Europe.

It seems judicious therefore, with the potential importance of protein-rich crops for replacing animal products in the future, to address this knowledge gap. Bridging this gap may provide a foundation for reactive future planning of European agricultural systems in the face of climate change. It may also provide a resource for encouraging greater production of protein-rich crops in European agriculture.

1.8 Research Objective

The magnitude and complexity of studying land use changes, ecosystem conservation, rural livelihoods, and food production suggests the need for a multi-scalar methodological approach. Such a methodology should have the capacity to incorporate and analyse drivers, impacts, and trade-offs, but also allow for the identification of social, political, and economic responses to improve them or ameliorate their impacts. This approach should also provide a platform for

incorporating the perspectives and inputs of stakeholder groups. From this research, it is hoped that an integrated and contemporary perspective of deforestation, food production, and ecosystem service trade-offs can be derived, whilst further illuminating the socio-natural inter-linkages of these processes.

To respond to this, the overall objective of this research is to analyse the role of socio-economic, environmental, and institutional factors in Latin American and Caribbean deforestation, whilst investigating historical trends in consumption and production patterns of protein-rich products, and outlining strategies for the future to address these changes in the European Union.

The specific objectives of the research can be summarised as follows:

- To develop and implement an interdisciplinary methodology to analyse deforestation, ecosystem service trade-offs, and food production, incorporating the multi-scalar problems and the dynamic interactions that take place between the drivers, causes, and impacts of these processes.
- To quantify how multi-scale socio-economic conditions can drive or inhibit the vulnerability of forests to deforestation at multiple scales across Latin America and Caribbean countries.
- To analyse the balance between socio-economic development and environmental conservation in agricultural-forest systems of Latin America at the farm scale, assessing the particular role of decision-makers and policy implementation in affecting this balance.
- To evaluate global and continental dietary changes, identify current barriers and opportunities for consumption and production shifts, and define potential strategies for future consumption changes across the European Union.
- To explore the potential of protein-rich crops, as replacements of animal products as part of these consumption changes, under future climates across the European Union
- To identify potential actions and strategies that could be implemented to improve long-term environmental and socio-economic conditions within deforesting nations, or in regions exerting indirect deforestation pressure to reduce pressures.

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The methodology applied in this research presents a novel combination of methodologies to address the aforementioned objectives. The benefits of implementing such an approach are hoped to allow for an enhanced understanding of land-use change, food production, rural livelihoods, and ecosystem conservation.

2.1 Methodological Framework

The combined methodology addresses the multiple dimensions of deforestation, accounting for the role of socio-economic development in forest vulnerability at continental, national and state scales, but also the impact of decision-making and policy development in exacerbating or inhibiting ecosystem services trade-offs at the farm-scale. This is then combined with analyses considering the trends of global consumption and production of protein rich products and the development through stakeholder interactions of potential strategies for transitioning future consumption and production patterns. Analysis is then made of the potential of production of protein-rich crops under future climates.

The research approach selected to achieve the objectives of this investigation implements distinct methods for addressing the multi-dimensionality of the problem, by moving progressively down scales to analyse in-situ issues, before moving back out on this scale. At each step of this process, distinct methodologies are applied and include:

1. *Quantification of forest vulnerability to deforestation based upon socio-economic factors at the national and state level: index development*

The investigation starts with an extensive analysis of the literature dedicated to the socio-economic drivers and causes of deforestation. This is used as a foundation for the quantification of national and state vulnerability of forests to deforestation driven by socio-economic factors. To quantify such vulnerability, a composite index is developed, where variables demonstrated by the literature to drive or cause deforestation in Latin America and the Caribbean are incorporated. Selected variables are weighted based upon surveys with experts and participatory methodologies with stakeholders. Application of the index at both the national and state scale (in selected case studies) across multiple years provides temporal and spatial trends of vulnerability, and can be used to highlight regions of high vulnerability for further analysis.

2. Analysis of the role of decision-making in farm-scale trade-offs between forest conservation and agricultural expansion: multi-objective goal programming

Analysis of national and state scale vulnerability may provide improved understanding of the impacts of socio-economic development. However, it cannot offer an insight into the role of lower-scale decision-making in these processes. To address this, a farm-scale mathematical programming model was developed, applying multi-objective goal programming (MOGP) across a series of representative farms in a selected case study (Department of Santa Cruz, Bolivia). The model analyses the relationship between two potential farm-scale ecosystem service goals: net farm income and net farm carbon sequestration. The model further permits the analysis of the role of decision-making in these relationships, through parametric changes to preference weights for achievement of each goal. The use of this model allows for the application of two policy scenarios: Conservation of Ecosystem Services and Socio-Economic Development. These scenarios were developed to identify how the ecosystem service relationships and the role of decision-makers might alter under the conditions of opposing policy scenarios developed to encourage ecosystem service conservation and socio-economic development.

3. Identification of global and continental trends of animal product consumption and exploration of strategies for attaining desirable future consumption and production changes: trend analysis and participatory assessment

To identify how consumption and productions trends of protein-rich products (animal and vegetable) have evolved in recent decades across the world trend analyses of consumption and production at global, continental, and national scales is presented. This is combined with participatory analyses to: identify current barriers and opportunities for plant-protein consumption and production in the European Union; develop potential strategies for achieving desirable consumption and production futures in the EU. These participatory analyses were developed through interactions with pan-European stakeholders.

4. Modelling how future climate change may affect one of the principal solutions cited to reduce deforestation at the national-scale: biophysical crop modelling

Finally, as a means of measuring the potential for meat replacement products in the EU under future climates, a crop suitability model is developed and applied to a group of protein-rich crops. Climate change may have an important role in defining which potential crop options might be suitable for farmers in the future across the EU. This analysis identifies climate change impacts at national scales, whilst also suggesting the best protein-rich crop options for production at landscape (4 km²) scale.

Figure 4 summaries the methodological framework of this research.

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Figure 4. Methodological framework of thesis investigation.

2.2 The Areas of Study

The multi-dimensionality of the challenges facing Latin American and Caribbean forests, as outlined above, infers the need for a dynamic approach to analyse the process of deforestation, ecosystem conservation, rural livelihoods, and food production at multiple scales and from various perspectives. Such an approach will assist in providing a more resolved and diverse analysis, attendant to the complexity of the problem. As such, the methodology will be developed at global, continental, national, state, and farm-scales.

Continental

At the continental scale, the wider drivers and patterns of deforestation are addressed to provide a context for more detailed and downscaled analyses that follow. At this scale, forest vulnerability across Latin America and the Caribbean will be quantified during the period 2000-2010. Further, at this scale trends of historical protein products consumption and production will be outlined for the period 1961-2013. Future strategies for achieving consumption and production changes will also be assessed at the continental scale.

National

Moving down the scales, the majority of the focus of this investigation will be based at the national scale. At this scale, temporal patterns of vulnerability to deforestation stemming from socio-economic factors will be analysed for all LAC countries. Analysis of vulnerability at this scale will permit mapping of temporal and spatial trends, within the wider context of continental patterns. This national scale approach will also be applied to examine consumption and production trends of protein products across EU Member States (MS). This scale will also be used to investigate the response of protein-rich to the conditions of future European climates.

State

To derive more resolved conclusions of the role of socio-economic processes in driving vulnerability in Latin American forests, three state (sub-national) case studies were developed: The Department of Santa Cruz (Bolivia), the State of Pará (Brazil), and the State of Jalisco (Mexico). Each case study is highlighted in dark grey in Figure 5. These case-studies were also selected as part of the ROBIN project. Each case study site, although distinct, does share many characteristics: seeing high levels of land-use change in recent years, economically dependent upon agricultural activities, low-levels of socio-economic development, and high population growth. More detailed information for each of these case-study sites is provided below:

Figure 5. Case study sites

Note: The Department of Santa Cruz (Bolivia), the State of Pará (Brazil), the State of Jalisco (Mexico) all in darkest grey. The Province of Guarayos (blue) within the Department of Santa Cruz.

The Department of Santa Cruz

The Department of Santa Cruz (DSC) is the largest of Bolivia's 9 departments. It represents roughly a third of Bolivia's land surface area (370,621 km²). The population of DSC has grown 30%, at a rate of 2.6%/year since 2001, to 2.65 million inhabitants (Instituto Nacional de Estadística [INE], 2012a). The DSC is one of the most developed of Bolivia's departments, with a HDI value of 0.689 (United Nations Development Programme [UNDP], 2004). Despite this, the department suffers from high and increasing levels of poverty, with 35.5% of the population living below the poverty line in 2012, increasing from (31.8%) in 2001 (INE, 2001; INE, 2012a). The department also sustains high levels of official unemployment, with only 49.2% of the working age population in work (INE, 2012a). The biggest employers in the department are commerce and transport (27%), non-specified employment (26%), and agriculture (15%) (INE, 2012a).

The importance of Santa Cruz to Bolivian agriculture is considerable, with the DSC accounting for 70.1% of Bolivia's cultivated area (INE, 2017a). Crop cultivation covers 6.9% of the department's land surface area, more than doubling in the 15 years from 2001-2016 to 25,519 km² (Figure 6a). Soya is the most widely cultivated crop, occupying 1.3 Mha, or 51.9% of the department's arable land area. This represents a doubling in soya cultivated area from the

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0.61Mha cultivated in 2001 (Figure 6b) (INE, 2017a). Other important crops within the department are highlighted in Figure 6b and include sorghum (0.29 Mha), maize (0.19 Mha), sunflower (0.15 Mha), sugarcane (0.14 Mha), and rice (0.13 Mha). Beyond arable land, grasslands cover 36,342 km² (INE, 2015a), with total cattle numbers almost doubling to 3.8 million (Figure 6c), with particularly rapid growth seen from 2008-2012 (INE, 2017a).

Figure 6. Land use and agricultural activities in the Department of Santa Cruz, Bolivia.

Data Source: INE (2017a)

In 2001, Santa Cruz was widely forested with forests covering 70% of the land surface (Prefectura del Departamento de Santa Cruz, 2007). Following the findings of the 2013 National Agricultural Census, it was estimated that only 51% of the DSC included within the census remained forested, equating to 71,678 km² (INE, 2015a). These figures, coupled with Figure 6a and Figure 6b, along with the recent findings of the agricultural census suggest the decline in forest coverage across the department. Series data for forest area in the department was unattainable.

The State of Pará

The state of Pará is the second largest of Brazil's 27 states, accounting for 15% of Brazil's surface area (1.25 million km²). The estimated population in 2017 was 8.36 million, increasing from 7.58 million in 2010, with an annual growth rate of 1.5% (Instituto Brasileiro de Geografia y Estadística [IBGE], 2017). Roughly a third of the population live in rural areas. Pará is one of the least developed states in the country ranking 24/27, with a HDI value of 0.646. It also has one of the

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lowest nominal per capita incomes of ~\$2000 (USD) (IBGE, 2017). In 2014, 23% of the population lived below the poverty line, reducing from 31% in 2008 (Fundação Amazônia de Amparo a Estudos e Pesquisas [FAPESPA], 2016). Despite this, Steward (2007) found that many socio-economic improvements within the state bypass the poorest of the state. 52.5% of the population over the age of 10 were found to be economically active, marginally lower than the Brazilian average of 57.7% (IBGE, 2017). Of the population in official employment, only 5% were employed in agricultural activities (FAPESPA, 2017). Despite this low employment figure, the true value of agriculture in the state can be observed by its economic contributions to the state's GDP, contributing 11%, increasing from 10% in 2010 (FAPESPA, 2017).

Figure 7. Land use and agricultural activities in the State of Pará, Brazil

Data Sources: IBGE (2009); FAPESA (2017)

As of 2015, arable land in Pará (Figure 7a) covered 1.26 Mha, increasing from 1.05 M ha in 2011. Temporary crops contributed more than 80% to this figure (FAPESA, 2017). Soya is Pará's most widely produced crop, occupying 0.34 Mha (27% of arable land), more than trebling since 2010 (0.10 Mha) (FAPESA, 2017). The most recent figures (Figure 7b) show that other important crops within the state include cassava (0.31 Mha), maize (0.23 Mha), and rice (0.06 Mha) (FAPESA, 2017). In 2006, the official agricultural census of Brazil found that grasslands covered 11.6 Mha (IBGE, 2009). Total cattle increased by 11% from 18.2- 20.3 million during the period 2011-2015

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(Figure 7c) (FAPESA, 2017). These contemporary values represent a dramatic increase from the 13.9 million cows identified in the agricultural census of 2006 (IBGE, 2009).

loris (2016) found that Pará has a long history of deforestation, migration and conflicts, relating to agricultural activities. Simmons (2004) suggests these conflicts stem from the state's resource wealth. In 2000, Pará was 74% forested, covering 0.93 million km² (Instituto Nacional de Pesquisas Espaciais [INPE], 2017). By 2016, forest cover had reduced to 70% (0.87 million km²) (Figure 7d) (INPE, 2017). During this same period, deforestation rates were found to have declined from a peak of 11,271 km² in 2003, to 1784 km² in 2014. However, in 2015 and 2016 this rate rose for the first time in a decade, in 2016 standing at 2693 km² (INPE, 2017).

The State of Jalisco

The State of Jalisco (SOJ) is the 7th largest of Mexico's 31 states, occupying roughly 4% of the national land surface area (80,228 km²). The SOJ's population grew 7% to 7.84 million, during the period 2010-2015 (Instituto Nacional de Estadística y Geografía [INEGI], 2018a). In 2010, the SOJ had lower than average socio-economic development, with a HDI value of 0.673 (INEGI, 2018a), whilst the national value stood at 0.745 (UNDP, 2016). In 2016, 31.8% of the population lived in conditions of poverty, with 1.8% in extreme poverty (INEGI, 2018b). Despite this, the SOJ had one of the highest per household incomes of \$7,724 in 2014 (INEGI, 2018b). As of 2014, 61.6% of the working population was found to be economically active, higher than the national average of 59.1% (INEGI, 2018b). Of the working population, 5.3% were employed in agricultural activities in 2014, increasing from 4.7% in 2010 (INEGI, 2018a).

Figure 8. Land use and agricultural activities in the State of Jalisco, Mexico

Data Sources: SIAP (2018a); SIAP (2018b); SIAP (2018c); CONAFOR (2014)

In 2016, 1.64 Mha of SOJ was covered by arable lands (Figure 8a), increasing from 1.53 Mha in 2004 (Servicio de Información Agroalimentaria y Pesquera [SIAP], 2018a). This represents roughly 20% of the SOJ's land surface area. The majority of this land is dedicated to temporary crops, with 0.46Mha of maize cultivated in 2016 (SIAP, 2018b). Other important crops in the state are sugarcane (0.09Mha), wheat (0.03Mha), and sorghum (0.02Mha) (Figure 8b). Total cattle in the SOJ increased from 2.6 to 3.1 million over the period 2006-2015 (SIAP, 2018c) (Figure 8c).

In 2013, SOJ was 52% forested, with the state's forests covering 0.04 million km² (Comisión Nacional Forestal [CONAFOR], 2014). Forest cover across the SOJ reduced by 6% since the turn of the millennium (CONAFOR, 2014) (Figure 8d).

Municipal/Farm

At this scale, the impacts of climate change on protein-rich crops across the European Union will be analysed, with results derived at a resolution of 4 km². Further, to deliver a more resolved analysis of the trade-offs associated with socio-economic development and environmental degradation at more localised scales, one municipal (sub-state) case study site was selected within a forest frontier community of the Amazon basin: The Province of Guarayos (Santa Cruz, Bolivia) highlighted in blue (Figure 5).

The Province of Guarayos

The Province of Guarayos (POG) is one of the DSC's largest provinces, covering 32,810 km² (INE, 2015b). The population of the POG almost doubled between 2001 and 2012 to 48,301, with annual growth of 3.1% (INE, 2012b). More than 50% of the populace is under the age of 18 (INE, 2012b), with school attendance rates of 85%. Unlike the DSC, the POG is far more dependent upon agricultural activities in terms of employment and economic development, with 49.5% of population employed in agricultural activities, representing the biggest employer of the province (INE, 2015b).

As with the DSC, agricultural activities dominate land-use, with arable land covering 1,319 km², or 4% of the province's land surface area (INE, 2015b). Of this arable land, soya dominates both winter (37%) and summer (38%) cultivation, with sunflower (28%), maize (13%), and sorghum (10%) being important winter crops, whilst rice (36%) and maize (18%) are secondary summer crops (INE, 2015b). Pastures are also an important agricultural activity within the province, with 24% (2,291km²) of the census area being grassland, with cattle stocks of 0.22 million (INE, 2015b).

Forest area, like in the DSC is the principal land cover, with 52% (9,404 km²) of the area recently included within the national agricultural census being forest. Furthermore, a lack of management strategies and conservation policies have been identified as causing reductions in local biodiversity, depleted natural resources and high levels of deforestation across the POG (Varela-Ortega et al., 2014).

2.3 Methodological Review

Mildrexler et al. (2016) highlight potential options available for the development of a forest vulnerability analysis, through index development. The utility of indices in vulnerability research has been emphasised by Beroya-Eitner (2016), as they can incorporate a wealth of information and provide concise and easily understood information. Composite index development and the implicit inclusion of multiple variables offers advantages over individual indicators as they can provide a more representative image of the modelled reality (Vincent, 2004). Indices also offer the potential for spatial and temporal comparisons to be made (Mildrexler et al., 2016) and permit constant and easy refinement to improve validity (Vincent, 2004). Gesellschaft für Internationale Zusammenarbeit (GIZ) (2013) and Varela-Ortega et al. (2014) both suggest that to better understand forests, and their future, there is a fundamental need to investigate the role of socio-economic factors and how their interactions can affect forests.

Trade-offs in ecosystems services and socio-economic development and environmental degradation have been analysed and described through the application of an array of support tools and methodologies (e.g. Polasky et al., 2008; Giller et al., 2011). In many cases, the application of optimisation methods have been implemented to maximise the utility of one, or multiple resources or services, then measuring the impacts upon others (Groot et al., 2012). One often used approach is multi-objective goal programming (Charnes et al., 1955). Goal programming (GP) allows for the development and solving of multiple, often contrasting objective problems through optimisation programming (Kaiser and Messer, 2011). As part of this methodology, goals are set as target values, with the achievement function of the model limiting negative deviations from these values. GP has been widely applied in resource management (Groot et al., 2012; Diaz- Balteiro et al., 2013; Aldea et al., 2014) to demonstrate how achievement of decision-maker derived goals can diffuse through a system and result in differential impacts. Optimisation methods also permit the incorporation of scenarios (Dogliotti et al., 2005), which can highlight the impacts of systemic changes upon the trade-offs and measured indicators (Fisher et al., 2011; Kanter et al., 2016a). The potential of GP is evident for trade-off analysis and has been widely implemented (e.g. Groot et al., 2012; Schroder et al., 2016). The utility for ecosystem service trade-off analyses is further evident by their ability to identify optimal management solutions for achievement of conflicting ES based goals, whilst potentially reducing local development conflicts (Dearing et al., 2012; White et al., 2012; Carrasco et al., 2014).

Consumption changes have been addressed through implementation of an assortment of methodologies. Popkin (1997) applied regression analysis to identify the link between socio-economic factors and dietary transitions towards increased consumption of animal based products. Delgado (2003) implemented trend analyses to demonstrate the acuteness of these changes in developing regions. de Boer et al. (2006) through the application of principal component analysis exposed the presence of these changes across developed regions, whilst Vranken et al. (2014) using regression analysis, may have highlighted the ultimate pathway of these trends. Imamura et al. (2015) used national consumption surveys to demonstrate that animal product consumption is increasing across most of the world. Although national food consumption surveys provide the most reliable and detailed consumption data for such studies, the lack of concrete methodologies and limited coverage often limits their utility for international comparative analyses (Kearney et al., 2010). In most cases, publicly available databanks are the source of data for these studies. Although the use of open access databanks, like the FAO's Food Balance Sheets (FBS) are problematic, in terms of their potential overestimation of consumption (Kearney et al., 2010), they are considered the most reliable data sources for trend analyses like those applied by Delgado (2003).

In investigating idealised consumption and production futures like those condoned in the literature (e.g. Cassidy et al., 2013; Springmann et al., 2016) and to develop potential strategies for their achievement, the development of normative scenarios can be useful (Börjeson et al., 2006). Backcasting (Robinson, 1982) offers such a scenario based methodology, examining the mechanisms for attaining desirable futures (Dreborg, 1996; Robinson, 2003; Kok et al., 2011). Backcasting develops a normative vision of the future and works backwards from a desired future goal, with milestones and policy actions identified, and potential strategies for attaining the goal developed (Robinson, 1982; Robinson, 2003; Salter et al., 2010). Backcasting offers a useful tool for elucidating transitional pathways for shifting consumption in the future and has been extensively used for sustainable lifestyle choices (Neuvonen et al., 2014), agricultural planning (Kanter et al., 2016b), food security (Vervoot et al., 2014), but has yet to be applied to for analysing dietary transitions. Further, inclusion of stakeholder perceptions, through participatory backcasting, provides an essential attribute for such a complex problem as dietary protein transitions (de Bakker and Dagevos, 2010).

Extensive overviews of climate based crop modelling can be found in Ewert et al. (2015) and Fernández (2017), in each case they identify three approaches for crop modelling: biophysical (Jones et al., 2011), agro-ecosystem models (Fischer et al., 2002), and historical analyses (Lobell and Burke, 2010). Climate change analyses that have largely concentrated upon biophysical aspects have approached climate change analysis by invariably considering yield impacts upon globally important crops (maize, wheat, soya, and rice) (Lobell and Gourdji, 2012; Rosenzweig et al., 2014; Challinor et al., 2014). However, these analyses have largely ignored the impacts upon lesser crops. Other biophysical crop-modelling options also exist that measure impacts of climate change not through yield changes, but through changes in suitability to a given environment or abiotic variables. The utility of such an approach is highlighted by Manners and

van Etten (2018), where they suggest these models can provide an approximation of climate change impacts in situations where more detailed modelling activities are missing or difficult to implement. The value of such approaches is also evident for agricultural planning (Foley et al., 2005; Zabel et al., 2014), identification of adaptation requirements (Jarvis et al., 2012), and detecting potentially highly suited, but uncultivated crop species for a particular region (Beebe et al., 2011). The mechanistic suitability model EcoCrop (Hijmans and Elith, 2017) represents one such tool, determining crop suitability based upon expert derived crop-specific climatic parameter ranges. Ramirez-Villegas et al. (2013) found that the outputs of this relatively simplistic model to be largely consistent with more complex crop models. Despite its simplicity, the utility of its outputs is evident in its widespread application, deriving climate change impacts upon multiple crops and crop groups across the globe (Jarvis et al., 2012; Ramirez-Villegas et al., 2013; Piikki et al., 2017).

2.4 Investigating Deforestation Vulnerability: Composite Index Development

The investigation starts with an in-depth analysis of the literature dedicated to the socio-economic drivers and causes of deforestation. This is used as a foundation for the quantification of national and state vulnerability of forests to deforestation driven by socio-economic factors. To quantify such vulnerability, a composite index is developed, where variables identified by the literature to drive deforestation are incorporated. Selected variables are weighted based upon surveys with experts and participatory methodologies with stakeholders. Application of the index at both the national and state scale (in selected case studies) across multiple years offers both temporal and spatial trends of vulnerability, to highlight regions of high vulnerability.

A schematic representation of the methodology applied in the development of the Deforestation Vulnerability Index (DVI) is presented in Figure 9. The DVI follows a standardised method of index calculation (García de Jalón et al., 2014; Naumann et al., 2014).

Figure 9. Methodology applied in the development of the Deforestation Vulnerability Index.

Identification of Factors Responsible for Forest Vulnerability

The development of the index concentrated upon socio-economic drivers and causes of deforestation identified within LAC countries. 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 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) as part of the project ROBIN. A workshop was performed in each of the state-scale case study sites of this investigation (See Section 2.3- State): The Province of Guarayos (DSC, Bolivia), Tapajós National Forest (Pará, Brazil), and Cuitzmala River Basin (SOJ, Mexico).

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, unenforced policy, and poor governmental coordination were identified by both the literature and stakeholders as causal factors of deforestation (Table 1).

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Table 1. Drivers of deforestation identified from literature review, and enriched by findings from stakeholder workshops performed as part of the EU project ROBIN.

Driver/cause of Deforestation	Country(ies) where Identified	Scale of research	Literature Review		Local Stakeholder Workshops	
			Examples of Articles	Examples of Methodologies Used in Identification	Identified in Stakeholder Workshop	Country(ies) where Identified
Agricultural Expansion (incl. grazing expansion)	Argentina, Bolivia, Brazil	National, Provincial,	Macedo et al., 2012; Müller et al., 2012; Richards et al., 2012; Guida Johnson and Zuleta, 2013; Paneque- Galvez et al., 2013;	GIS Analysis, Field Survey, Census Analysis, Econometric Analysis	Yes	Bolivia, Brazil and Mexico
Currency Exchange Rates	Argentina	Provincial	Gasparri and Grau, 2009	GIS Analysis	No	-
Economic Development	Bolivia, Brazil, Peru	Provincial	Angelsen and Kaimowitz, 1999; Killeen et al., 2008; Southworth et al., 2011; Aide et al., 2013	Field Survey, GIS Analysis	No	-
Education Level	Belize, Haiti, Mexico	National	Chowdhury, 2006; Alix-García, 2007; Dolisca et al., 2007; Wyman and Stein, 2010.	Community Survey, Econometric Analysis	Yes	Mexico
Exchange Rates/ Currency Values	Bolivia, Paraguay	National	Richards et al., 2012	Economic Model	No	-
Forest Cover	Panama	Local	Rudel and Roper, 1997; Sloan et al., 2008	GIS Survey, Household Survey	No	-
Gold Prices	Peru	Local	Swenson et al., 2011	GIS Analysis	No	-
Immigration	Bolivia, Brazil	Provincial	Fearnside, 2001; Steininger et al., 2001; Killeen et al., 2007	Policy Review, GIS Analysis	Yes	Bolivia
Infrastructure Development	Belize, Bolivia, Brazil, Peru	Provincial	Wyman and Stein, 2010; Southworth et al., 2011; Bottazzi and Dao, 2013; Perz et al., 2013; Barber et al., 2014	GIS Analysis, Census Analysis, Field Analysis, Community Surveys	Yes	Brazil and Mexico
International Soybean Demand	Argentina, Brazil	Local, Provincial	Gasparri and Grau, 2009; Walker et al. 2009; Barona et al., 2010; Arima et al., 2011; Verburg et al., 2014	Economic Modeling, GIS Analysis, and Literature Review	Yes	Brazil and Mexico
Land Prices	Costa Rica	Provincial	Roebeling and Hendrix, 2010	Economic Modeling	No	-
Land Tenure	Bolivia, Brazil, Ecuador,	Provincial, National	Liscow, 2013; Paneque-Galvez et al. 2013; Perz et al., 2013; Holland et al., 2014	Census Analysis, Community Survey, Econometric Analysis, GIS Analysis	Yes	Bolivia
Mismanaged and Unenforced Policy	Bolivia, Brazil, Mexico	Local, Provincial	Durán et al., 2011; Redo et al., 2011; Verburg et al., 2014.	Economic Modeling Field Survey, GIS Analysis	Yes	Bolivia and Brazil
Population Density	Brazil, Colombia, Mexico	Local, Provincial	Armenteras et al., 2006; Kirby et al., 2006; Bonilla- Moheno et al., 2012	GIS Analysis	No	-
Population Growth	Argentina, Brazil, Haiti, Mexico	Provincial	Angelsen and Kaimowitz, 1999; Dolisca et al., 2007; Porter-Bolland, 2007; Grau et al., 2008	Economic Modeling, Community Survey, GIS Analysis	Yes	Brazil
Poor/ Uncertain Policy	Continent Wide	Provincial, National,	Fearnside, 2001; Culas, 2007; Zwane, 2007; Gasparri and Grau, 2009; Redo et al., 2011; Paneque-Galvez et al., 2013	Econometric Analysis Field Survey, GIS Analysis, Household Survey Policy	Yes	Mexico
Weak and Poorly Co-ordinated Governmental	Continent Wide	Provincial, Continental	Bulte et al., 2007; Culas, 2007; Barsimantov and Navia- Antezana, 2012	GIS Analysis, Field Survey, Econometric Analysis	Yes	Bolivia and Brazil

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.

Table 2. List of 13 indicators of forest vulnerability selected for the index.

Indicator	Description	Source
Gross Domestic Product (GDP) per Capita	Per capita value of products and services produced.	World Bank
Growth in Agriculture Value Added	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 agricultural.	Own Formulation
Population Density	People/km ² 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/100km ²)	Ratio of the length of the country's road network to the country's	World Bank

Note: Indicators selected based upon literature review, stakeholder workshops, and data availability. Land area defined as total country area minus standing water.

State Scale Index Development

To test its multi-scalar applicability, the DVI was also applied on the 3 state-scale case studies of this investigation. Where possible, indicators used in the state index were identical to those of the national index (Table 2). GDP (Price Purchasing Parity) per capita was unobtainable at the state scale; therefore state GDP (constant 2005 USD (United States Dollar)) data was used. National governance data were applied at the state scale, as no sub-national data were available. The majority of available state data were found to be for the period 2008-2011. To address this, the state index was developed only for the year 2010.

To compare state and national results, national scale data was also collected for the aforementioned state index indicators. Data were collected for all 24 countries. To reduce the potential of exaggerated vulnerability results stemming from normalisation over a small dataset (3 states and 3 countries), the state index indicator data was normalised using data for all 24 countries and the 3 states. Comparative analysis between national and state results is presented only between the 3 analysed states, and their respective countries.

State 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.

Calculating the Deforestation Vulnerability Index

The 13 indicators selected for developing the index (Table 2) were normalised to ensure identical value ranges (0-1), where 0 is equal to low vulnerability and 1 high. Normalisation of indicators (equation 1) considered the maximum and minimum value of each indicator across all countries (and states).

$$Rx_{ij} = \frac{(x_{ij} - \text{Min } x_i)}{(\text{Max } x_i - \text{Min } x_i)} \quad 1$$

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 Min and 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-Antezana, 2012; Varela-Ortega et al., 2014), and regulatory quality (Verburg et al., 2014; FAO, 2015c). Therefore, to incorporate these potentially inhibitory effects, these indicators were normalised as shown in equation 2.

$$Rx_{ij} = 1 - \frac{(x_{ij} - \text{Min } x_i)}{(\text{Max } x_i - \text{Min } x_i)} \quad 2$$

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 Min and 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 state) vulnerability value.

$$DVI_j = \sum_{l=1}^{13} Rx_{ij} W_l$$

3

Where DVI_j is sum of all weighted indicators in j th country, $Rx_{ij} W_l$ is the weighted vulnerability contributed by the i th normalised indicator in the j th country, multiplied by the l th weighting scheme.

Weighting the Index

Arrow (1963) suggests that there remains to be one recognised means of weighting an index. To address this, two weighting schemes (expert and stakeholder) were applied. 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 state indices, as surveyed experts were familiar with the states 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. The number of times a factor was mentioned as driving deforestation in each workshop was used, 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 three stakeholder weights were developed, one for each state. As part of the state index these stakeholder weights were only applied to the state and country where they were developed.

An equal weight, which gave each indicator the same proportional weight of 0.08 (1 divided by 13) was also developed and applied. 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.

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).

Robustness and Sensitivity of 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 (Organisation for Economic Co-operation and Development [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 1,000 outputs of the index using random weights generated from probabilistic density functions within the index calculation (Naumann et al., 2014; García de Jalón et al., 2014). This analysis was performed only for 2010 data.

2.5 Analysing Ecosystem Service Trade-offs: Multi-objective Goal Programming

Moving down the spatial scales and to broaden the spatial perspective of this investigation a farm-scale mathematical programming model was developed. This model applied multi-objective goal programming (MOGP) across a series of representative farms characterised from fieldwork within the municipality/farm-scale case study- Province of Guarayos, Bolivia (Figure 5). As mentioned in Section 2.2, the province is highly dependent upon agriculture for economic development and employment and has seen dramatic environmental degradation over recent years. In spite of the abundance of natural resources, the Province of Guarayos is one of the poorest within the department, with low levels of economic activity and below national average levels of education (INE, 2011).

The model reproduces farmer's behaviour under different constraints. In particular, reproducing the effects of parametric changes to preference weights for achievement of two farm-scale goals: net farm income and net farm carbon sequestration. The outputs of this model demonstrate the impacts of such weighting changes in achievement of the two goals, resource allocations, cropping options, and ecosystem services, simulating the role of hypothetical decision-makers and goal preference can have in inhibiting or aggravating farm-scale trade-offs. The scale of achievement of one goal, versus the cost to the other goal were used to quantify farm-scale trade-offs. A series of policy scenarios were applied to identify how such decision-maker based trade-offs might alter under the conditions of policy scenarios developed to inhibit the extent of trade-offs.

Province of Guarayos Field-work

As part of the ROBIN project, field-work was performed across the province in November 2013, with 31 semi-structured interviews performed with randomly chosen farmers. Farmers were asked a range agronomic, economic, and social questions relating to their farm, agronomic practices, and perceptions of the current situation within the area. Farms ranged from less than 1ha (subsistence) to more than 500ha (industrial), with the surveyed area exceeding 4500ha (~0.2% of the province). Three clear groupings of farms were found: less than 100ha (representing the greatest proportion), 100-250ha, and a lesser group of more than 250ha. In each group, varying proportions of cultivated and forested areas were observed, with smaller farms having broadly the greatest proportion of forest. Farmers in these smaller holdings suggested a lack of access to credit and machinery limited their ability for more extensive forest clearances. This limitation was not found in the larger holdings. In general, farms cultivated at least 2 crops, with higher crop diversity seen in smaller, subsistence holdings. The most common crops were maize, soya, bean, and rice. Subsistence farmers also cultivated pineapple, banana, and yucca. Notable seasonal rotations were evident in all farms.

National Census and Survey Data

The Bolivian Government recently published a general overview (INE, 2015c), along with limited data (INE, 2015b) from the 2013 National Agricultural Census, later publishing wide-scale data for the more limited Agricultural Survey of 2015 (INE, 2017b). In comparing the outputs of the field-work with the national survey data for the Province of Guarayos, very similar distribution of farm sizes, seasonal crop rotations, and cultivated/forested land proportions were identified. However, the field-work may under represent larger farms (>250ha), judging by their propensity within the survey. During the field-work it was especially difficult to interview the largest landowners within the region, due to them not being present or unable to partake due to cultural reasons (i.e. local Mennonite communities). Despite this and after reviewing both the census and the survey the field-work results are considered representative of the province in 2013.

Cluster Analysis

Using information collected from the field-work, surveyed farms were clustered using their inherent characteristics: farm size, cropped area, forest area, and crop diversity. Farms were clustered using the Hartigan-Wong (1979) method of k-means based cluster analysis, with farms grouped into three clusters.

Using these clusters, representative farm types were characterised using the agro-economic information for all farms within each cluster, collected during the fieldwork (Table 3). The values within the table represent mean averages, with standard deviations presented in italic parenthesis. These averages were derived from the farm data of all farms present within each cluster.

Table 3. Representative farm types of the Province of Guarayos.

Farm Type	Total Size (ha)	Cropped Area (ha)	Forest Area (ha)	Proportion of Farm Forested (%)	Cropping Pattern		
					Winter	Summer	Permanent Crops
Small	30 (26)	14 (18)	16 (17)	53 (37)	Bean (65%)	Rice (20%), maize (25%), soya (20%)	Banana (15%), pineapple (20%)
Large	204 (57)	102 (51)	102 (60)	50 (29)	Soya (65%), bean (35%)	Rice (45%), soya (30%), maize (25%)	-
Very Large	547 (153)	291 (290)	256 (126)	47 (29)	Maize (100%)	Soya (50%), maize (35%), rice (15%)	-

Note: Farm types developed from k-means cluster analysis. Values are mean averages of data derived from fieldwork data. Standard deviation in italic parenthesis.

Farm-Scale Goals

As part of this analysis two farm-scale goals were defined: net farm income and net farm carbon sequestration. Data used to characterise and quantify these goals were collected from the field-work, the scientific literature, and The Economics of Ecosystems and Biodiversity [TEEB]

database (McVittie and Hussain, 2013). The TEEB dataset combines ES valuation data from the research literature.

Net Farm Income

Farm income, although not directly an ecosystem service included a series of provisioning ES (economically valued proxies) appropriated at farm-scales. These services include crop production, timber production, and forestry products (Table 4).

Crop Production: sum of the gross margin of crops cropped, multiplied by area harvested. Information for crop production was collected from the field-work. Crop production yields were multiplied by farm gate prices, with associated costs subtracted. The gross margin per hectare of crops differed by farm type and agronomic technique (intensive/ extensive). The agronomic data used were averages of all farms found within each representative cluster.

Deforested Timber: sum of timber sold as part of forest clearing processes for agricultural activities. Rights and Resources (2006) suggest the sale of timber is common within the province following deforesting activities. This can be a valuable income stream to rural households (Amacher et al., 2009). To define the value of timber sold, timber prices per hectare were taken from the TEEB database (McVittie and Hussain, 2013) and the Autoridad de Fiscalización y Control Social de Bosques y Tierra [ABT] (2017). An average timber price was set as a constant and multiplied by the area deforested.

Forestry Products: sum of forestry products available on each farm. The importance of forestry products to rural households (Angelsen et al., 2014) was also considered. These products are used in the daily lives of peoples within the Province of Guarayos, with plants harvested for traditional medicines and forest fruits and vegetables also gathered (Municipality of Ascension de Guarayos, 2006). Forests also represent important sources of protein, with hunting and fishing common (Municipality of Ascension de Guarayos, 2006). The price of raw materials are also included, which following conversation with farmers, they mentioned the utility of these materials for building, amongst other uses. Prices for these products were collected from the TEEB dataset (McVittie and Hussain, 2013). Data was only collected for data from Latin American tropical forests. Median economic prices (2013 USD) of these services were generated for food, medicine, and raw materials provided by forests.

The assumption was made that these services (Forestry Products) were only appropriated by farmers on the small and large farms. The very large farms were of industrial scales, with farming families largely not present and it was assumed that owners are not concerned with collecting fruits, vegetables, medicinal plants, nor hunting on holdings.

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Table 4. Farm-Scale Goal Information

Goal		Value	Unit	Source
Net Farm Income				
Crop Production	Crops	Crop, technique, and farm type dependent	\$/ha ^a	Field-work
Deforested Timber	Timber	75	\$/ha	Rights and Resources, 2006; Amachar et al., 2009; McVittie and Hussain, 2013
Forestry Products	Food	75	\$/ha	McVittie and Hussain, 2013
	Medicine	16	\$/ha	McVittie and Hussain, 2013
	Raw Materials	100	\$/ha	McVittie and Hussain, 2013
Net Farm Carbon Sequestration				
Mature Forest		3.5	t CO ₂ /ha/yr ⁻¹	Luyssaert et al., 2008; Peña-Claros et al., 2014
Reforested Forest		1	t CO ₂ /ha/yr ⁻¹	Peña-Claros et al., 2014
Deforested Land		-40	t CO ₂ /ha/yr ⁻¹	Harris et al., 2012; Achard et al., 2014
Cropped Land	Soya (Int) ^b	-1.21 ^c	t CO ₂ eq per t crop	Cool Farm Tool ^d
	Rice (Int)	-1.26		
	Rice (Ext)	-1.41		
	Beans (Int)	-1.68		
	Beans (Ext)	-0.52		
	Maize (Int)	-0.65		
	Maize (Ext)	-0.35		
	Sugarcane (Ext)	-1.25		
	Sorghum (Int)	-1.10		
	Banana (Ext)	-0.27		
	Pineapple (Ext)	-0.26		

^a \$ is measured in 2013 USD

^b Abbreviations in parenthesis Int (intensive farming—use of agrochemicals) and Ext (extensive farming—no use of agrochemicals)

^c Negative values represents emissions of CO₂eq, rather sequestration

^d Simple tool that can quantify on-farm greenhouse gas emissions and soil carbon sequestration based upon crop/farm specific agronomic and physical data inputs

Net Farm Carbon Sequestration

In contrast to farm income and recognising the climate regulating services performed by tropical forests (Brandon, 2014) and including the emissions from deforestation and agricultural activities, a net farm carbon sequestration goal was defined. This goal included carbon sequestration (CS) performed by mature and reforested forests as well as the emissions from deforestation events and agricultural activities (Table 4).

Mature Forest: total CS performed by mature forests. CS by mature forests was estimated using information collected from the literature (Luyssaert et al., 2008; Peña-Claros et al., 2014) and multiplied by forest area. Luyssaert et al. (2008) and Peña-Claros et al. (2014) defined that CS in mature forests can range from 2.4-4.5 t/ha; the average of these was taken to define CS of mature forests (Table 4).

Reforested Forest: total CS performed by reforested forests. Sequestration by reforested or secondary forests are also important sources of CS in tropical forests. The information from Peña-Claros et al. 2014 was used to define reforested CS (Table 4) and multiplied by reforested area. Recently reforested areas were assumed to immediately become sinks of CS.

Deforested Land: total carbon emissions from deforestation. To include carbon released from deforestation events, estimates from the literature were used (Harris et al., 2012; Achard et al., 2014). The literature suggests CO₂ emissions from deforestation range from 30-50 tonnes per hectare. The average from these two values was taken (Table 4). This value was multiplied by total deforested area. Emissions from deforestation were assumed to be instantaneous.

Cropped Land: total emissions from agricultural activities. The Cool Farm Tool (Cool Farm Alliance, 2016) was used to calculate equivalent carbon dioxide emissions from agricultural activities. This tool permitted the inclusion of CO₂ equivalent emissions from all facets of agriculture production: agro-chemical inputs, residue and soil management, and transport of crops to markets. Emissions differed based upon the agronomic techniques implemented in production. Farms clustered into the small farm were largely observed not to use agro-chemicals and little/no machinery. These observations therefore affected the emissions per hectare of crops on the small farm. Emission values were calculated per tonne of crop produced, multiplied by yields and areas harvested (Table 4).

Inclusion of CS from agricultural activities was also considered following the literature demonstrating its capacity (e.g. Lal, 2004; Managalassery et al., 2015; Powlson et al., 2016). However, as no farmers were observed to be performing soil management conservation methods agricultural based sequestration was excluded.

Model Development

An optimisation model using goal programming (GP) (Charnes et al., 1955) was developed for each of the three representative farms (Table 3). GP allows for the specification of multiple goals that can represent management objectives, subject to a series of constraints. The GP model specified a desired aspiration level (satisficing value) for each goal and then minimised the weighted sum of unwanted deviations from these values (Kaiser and Messer, 2011). Agronomic (e.g. yields, prices, inputs, land-uses) and labour data used for each of the models were derived from means of farms present in each cluster, as described in the previous section. All other information was calculated using values presented in Table 4.

Non pre-emptive GP was applied, which assumes that a decision-maker (DM) has a specific set of goals and that each goal can be weighted by preference with respect to the other(s) (Kaiser and Messer, 2011). The application of this type of model can be used to identify potential management solutions for achieving these goals, even in cases where goals are conflicting, demonstrating the utility of trade-off analysis (Schroder et al., 2016).

As noted by Varela-Ortega et al. (2014) agricultural expansion is expected to continue into the future across the province. These unstable conditions are expected to continue even under strict environmental policies and sustainable development conditions (Tejada et al., 2016). Therefore, to measure how these conditions might drive near-future trade-offs, the model was applied to determine ES relationships and the role of decision-making in 2025. The year 2025 was selected due to its relative temporal proximity to the data collected in the field-work (2013) and to offer a near future outlook of trade-offs and land uses across different farm types of the province. Prices and costs were assumed to be the same as in 2013.

Calibration

To develop an initially representative simulation of the Province of Guarayos, a calibrated model was developed mirroring observed agronomic information, characterised in Table 3. To perform such a calibration, Positive Mathematical Programming (PMP) was used as presented by Howitt (1995). Other approaches are available (e.g. Kanellopoulos et al., 2010). PMP was chosen due to its ability to generate realistic production activities and behaviour (Heckeley et al., 2012), calibrate exactly to observed data (Louhichi et al., 2013), respond easily to constraint changes, whilst not being constrained by weakly justified constraints (Heckeley, 2002).

As part of the calibration process (equation 4), a quadratic cost function was developed forcing reproduction of observed land-use on each of the three farm types (Table 1). The parameters of the cost function satisfying conditions of the optimisation model and its constraints. As part of the calibration farm income (equation 4) is maximised and is subject to farm sequestration (5), forest area (6), labour restrictions (7), permissible deforestation (9), farm area restriction (11), and minimum cropping area restriction (12).

$$\begin{aligned}
 \text{Max: } Z_g^* = & \sum_{c=1}^c \sum_{t=1}^t \sum_{s=1}^s (YI_{gcts} * PR_{gcts}) * X_{gcts} + (Dfo_g * TV) + (F_g * NTFV) - (Dfo_g \\
 & * Dfco) - (Rfo_g * Rfco) - \sum_{c=1}^c \sum_{t=1}^t \sum_{s=1}^s (\alpha_{cts} * X_{cts}) \\
 & + (0.5 * (\beta_{cts} * X_{cts}^2)) + (F_g * PES) + (Rfo_g * Rfpa) + (X_{gcts} \\
 & * SeMa_{gcts}) - (((X_{gcts} * emis_{ct}) + (Dfo_g * Demis)) * ETax)
 \end{aligned} \tag{4}$$

Calibrated Farm Income: where Z_g^* is total farm income, g is an index of the farm type (small, large, and very large), c is an index of crops, t is an index for agronomic techniques (intensive or extensive) and s is an index for season (summer or winter). YI_{gcts} : represents crops yields; PR_{gcts} : producer price for crops; X_{gcts} : area of land cultivated for each crop; Dfo_g : total farm deforested area; TV : the price of deforested timber sold; F_g : current forest area; $NTFV$: forest products value per hectare; $Dfco$: total cost of deforesting activities; Rfo_g : total reforested area; $Rfco$: cost of reforesting activities; α_{cts} is the marginal cost intercept, calculated from the variable costs for crops under different agronomic techniques and season, minus the dual values of the model constraints; β_{cts} is the marginal cost slope calculated from the square sum of the dual values of the calibration constraints under agronomic techniques and different seasons, divided by the observed surface area. The following only have values greater than zero in the policy scenarios. PES : payment for forest ecosystem services; $Rfpa$: payment for reforestation; $SeMa_{gcts}$: payment for seed and machinery costs; $emis_{ct}$: cropping emissions; $Demis$: deforestation emissions; $ETax$: emissions tax.

Subject to:

$$S_g^* = ((B0_g - Dfo_g) * MFS) + (Rfo_g * RFS) - (Dfo_g * DE) - \sum_{c=1}^c \sum_{t=1}^t \sum_{s=1}^s (X_{gcts} * CE_{cts}) \quad 5$$

Carbon Sequestration: where S_g^* is net farm sequestration; $B0_g$ is the observed area of standing area of forest derived from the cluster analysis; MFS is the amount CO₂ sequestered by mature forests; RFS is the amount of CO₂ sequestered by reforested forests; DE are CO₂ emissions from deforestation; CE_{ct} are CO₂ equivalent emissions from crop cultivation

$$F_g = (B0_g + Rfo_g) - Dfo_g \quad 6$$

Forest Area: where F_g is the total forest area.

$$LR_{gcts} * X_{gcts} \leq LFA_{gs} + LHI_{gs} \quad 7$$

Labour availability and balance restrictions: where LR_{gcts} : total labour requirements on each farm type for each crop under each agronomic technique and season, LFA_{gs} : total family labour on farm type g in season s; LHI_{gs} : total hired labour on farm type g in season s. All values are in hours.

$$B0_g - F_g = Dfo_g \quad 8$$

$$Dfo \leq MDef \quad 9$$

Deforestation Restrictions: where $B0_g$ is the observed area of forest cover; $Mdef$ is the maximum permissible area of deforestation per year in hectares.

$$F_g - B0_g = Rfo_g \quad 10$$

Reforestation Area

$$\sum_{c=1}^c \sum_{t=1}^t \sum_{s=1}^s X_{gcts} + F_g \leq FS_g \quad 11$$

Farm surface area: where FS_g is the total farm surface area in hectares.

$$\sum_{c=1}^c \sum_{t=1}^t \sum_{s=1}^s X_{gcts} \geq MCA * CA0_g \quad 12$$

Minimum Cropping Area: where MCA is a proportion vector of the total observed cropped area, set at 0.85; $CA0_g$ is the total observed cropped area in hectares.

Generating Satisficing Values

In developing a GP model, the inclusion of a DM allows for the assignment of satisficing values for each goal. However, as no DMs were directly involved, these values were developed following Fooks and Messer (2012) through maximisation of net farm income in equation 4, subject to equations 5-12, and through maximisation of net farm carbon sequestration in equation 5, subject to equations 4 and 6-12.

Multi-Objective Goal Programming

The goal programming model was defined (following calibration and generation of satisficing value), where the objective function (equation 13) minimises the under achievement (deviations) of the satisficing values of each goal. The undesired deviation factor, in this case (d_n^-) is divided by the satisficing values, resulting in negative deviation percentages and therefore representing comparable values for each goal (Fooks and Messer, 2012; Aldea et al., 2014). Each goal, Z_g^* (farm income), and S_g^* (farm sequestration) were maximised subject to these deviation factors (equations 14 and 15), and previous restrictions (equations 6-12).

As part of non pre-emptive goal programming, a DM can preferentially define weights for each goal (Kaiser and Messer, 2011). However, as no DM was involved a simulated weighting factor was applied (λ_n), with trade-offs in achievement of each goal due to weighting analysed through parametric changes in weights, increased/ reduced by 0.1 from the weighting extremes for net farm income ($\lambda=1$), to the contrary preference for net farm carbon sequestration ($\lambda=0$). This weighting factor allowed for the role of management strategy preferences of decision-makers in achieving the goals to be simulated and quantified.

$$\text{Min: obj} = \lambda_z \left(\frac{d_z^-}{Z_g^*} \right) + \lambda_s \left(\frac{d_s^-}{S_g^*} \right) \quad 13$$

Objective Function: where λ_n is a weighting factor for goal n ; d_n^- are negative deviations from goal n . The negative deviations (d_n^-) from the goals are limited through weighting (λ_n), based upon preference for the achievement of each goal with respect to the other and can be varied parametrically.

Subject to

$$\begin{aligned} & \sum_{c=1}^c \sum_{t=1}^t \sum_{s=1}^s (YI_{gcts} * PR_{gcts}) * X_{gcts} + (Dfo_g * TV) + (F_g * NTFV) - (Dfo_g * Dfco) \\ & - (Rfo_g * Rfco) - \sum_{c=1}^c \sum_{t=1}^t \sum_{s=1}^s (\alpha_{cts} * X_{cts}) + (0.5 * (\beta_{cts} * X_{cts}^2)) \\ & + (F_g * PES) + (Rfo_g * Rfpa) + (X_{gcts} * SeMa_{gcts}) - (((X_{gcts} \\ & * emis_{ct}) + (Dfo_g * Demis)) * ETax) \\ & - d_z^+ + d_z^- = Z_g^* \end{aligned} \quad 14$$

Income Goal Achievement: is identical to equation 1 and subject to the same constraints, but with the inclusion of achievement variables, where $(d_z^{-/+})$ measures the level of achievement of equation 13 relative to Z_g^*

$$((B0_g - Dfo_g) * MFS) + (Rfo_g * RFS) - (Dfo_g * DE) - \sum_{c=1}^c \sum_{t=1}^t \sum_{s=1}^s (X_{gcts} * CE_{cts}) - d_s^+ + d_s^- = S_g^* \quad 15$$

Carbon Sequestration Goal Achievement: is identical to equation 2 and subject to the same constraints but with the inclusion of achievement variables, where $(d_s^{-/+})$ measures the level of achievement of equation 13 relative to S_g^* .

Baseline

A 2025 baseline for each farm was developed minimising equation 13 subject to weighting factors. In generating the near future baseline, the restriction limiting deforestation (equation 6), defined through communication with farmers and local experts at CIAT (International Centre for Tropical Agriculture) at 3ha per annum was relaxed. This permitted a maximum of 36ha of deforestation to be performed, representing the 12 year period (2014-2025). Other restrictions were unchanged. This static model was only developed for the year 2025. As part of the baseline, payments for ecosystem services and reforestation, along with taxes on carbon (equivalent) emissions included in equation 14 were given values of zero. These values were altered as part of the policy scenarios, defined below.

Policy Scenarios

Two policy scenarios were developed simulating two rural development policy options: natural resource conservation and socio-economic development. The scenarios were implemented to identify their effects upon ES relationships and management preferences. The policy scenarios were designed in the context of the contemporary policy landscape of Bolivia, and considering policy options designed to encourage a positive future within the region developed from local participatory workshops, as part of the ROBIN project (Varela-Ortega et al., 2014; Varela-Ortega et al., 2015).

Conservation of ecosystem services (CES)

The Bolivian Government's desire for the protection of ecosystems is evident: the 'Mother Earth' law (Ley Nº 300 Marco de la Madre Tierra y Desarrollo Integral para Vivir Bien) aims to protect natural resources, whilst guaranteeing their restoration and regeneration (Article 4). Further, the Forest Law 1700 (Ley Forestal Nº 1700) promotes sustainable forest management, whilst securing the conservation of ecosystems and biodiversity. Local stakeholders were observed to largely support the fundamentals of these policies, whilst further suggesting the limitation of production activities and reforestation programmes as viable and socially acceptable future policies for ecosystem conservation within the region (Varela-Ortega et al., 2015). To further reflect the potential of reducing the environmental impacts of agricultural activities, the

potential for reducing agricultural emissions was incorporated through the application of improved crop and soil management techniques (Lal et al., 2004; Managalassery et al., 2015; Powlson et al., 2016).

The 'Conservation of Ecosystem Services' (CES) policy scenario was designed to encourage forest regeneration and more sustainable agricultural activities, deter excessive land use changes and provide financial assistance to cover foregone profits made from deforestation. The scenario consisted of:

- A payment for Ecosystem Services of \$175 per hectare of forest on the farm was offered. This value was developed considering Carrasco et al. (2014) and McVittie and Hussain (2013). Payment offered to subsidise foregone profits made from deforestation.
- A payment of \$150 per hectare of reforestation, covering costs and providing an incentive for reforestation activities.
- A tax of \$5 per tonne of CO₂ (or CO₂ equivalent) emitted.
- Application of zero tillage agricultural activities, reducing agricultural emissions by 0.5 tonnes of carbon per hectare (Lal et al., 2004; Managalassery et al., 2015; Powlson et al., 2016).

Socio-economic development (SED)

To propagate rural socio-economic development, the Bolivian government established the plan for development of the agricultural sector "Plan del Sector Desarrollo Agropecuario- Hacia el 2025" (Ministerio de Desarrollo Rural y Tierras, 2014), building upon earlier plans, which aimed to eradicate poverty, encourage food-security, transform land use, develop agricultural technology, and encourage sustainable agricultural practices. The fundamental structure of this plan was echoed by stakeholders, who considered that improvements in technical training, programmes to assist subsistence farmers and diversity in incomes could assist ecosystem conservation and encourage development in the future (Varela-Ortega et al., 2015).

The 'Socio Economic Development' (SED) scenario addresses the policy framework and stakeholders through reductions in barriers facing farmers in the region, whilst promoting greater incomes for rural communities. The SED scenario includes:

- Fully subsidised seeds, easing the burden of upfront costs on farms, along with access to farm machinery for free.
- Farms are permitted to deforest up to 70% of their present forest area but must conserve the remaining 30% of present forest area. However a tax of \$90 per hectare deforested is applied.

2.6 Exploring Consumption and Production Trends and Transitional Pathways: Statistical Trend and Participatory Analyses

To explore global, continental, national consumption and production changes, coupled with potential strategies for developed regions to encourage consumption and production changes a multi-scale methodology was developed. This methodology includes an initial data analysis investigating global, continental and EU past trends of production and consumption of protein-rich products, combined with a participatory analysis that incorporates two stakeholder workshops performed in the EU to elucidate the current situation of protein-rich crop production and consumption, and to develop sustainable pathways and identify policy requirement to encourage future shifts in protein-rich product consumption and production.

Data Analysis

To provide an overview of past trends in production and consumption of protein-rich products across the globe the following analyses were performed: (i) analytical description of per capita human consumption and total production of legumes and animal products for the period 1961-2013, at global and continental (Africa, Americas, Asia, Europe, and Oceania) scales, and aggregated for all EU-28 Member States (MS); (ii) analysis of the harvested area response of legume production to the Common Agricultural Policy (CAP) across the EU during the period previously analysed (1961-2013, and updated to 2015); (iii) map recent consumption and production changes across all EU-28 MS (1993-2013).

To develop the third analysis, 1993 was selected as a starting point to include EU MS such as Czechia and Slovakia (formerly Czechoslovakia), who previously did not have sovereign data. Average per capita consumption and total production values were calculated for each country and each product group (legumes and animal) across two 5 year periods: 1993-1997 and 2009-2013. The period 2009-2013 was selected as a 5-year period containing the most recent available data. 5-year averages were used rather than arbitrarily selecting a year, to avoid unrepresentative data caused by climatic conditions affecting production, or price or supply fluctuations reducing consumption. From these two averages, percentage changes were calculated across EU-28 countries and mapped.

Data Collection

Due to the scarcity and paucity of representative national scale household survey data to quantify consumption, consumption data from the FAO Food Balance Sheets (FBS) (FAO, 2016) was used. Aggregated data for food supply quantity (kg/capita/year) was collected for the period 1961-2013, first and last year available in dataset for each of the FAO defined continents (Asia, Africa, Americas, Europe, and Oceania) and global values. Data was also collected for all EU-28 MS. Due to the means in which continental aggregations are developed, European results may differ from EU-28 results, due to the inclusion of non EU-28 countries (e.g. Russia). Food supply represents the quantity of a product available for direct human consumption (processed or unprocessed) and does not include the quantity of the product available as feed. We interpreted this as a direct proxy for human consumption. Using the food supply data did limit the analysis

to legume groups (beans, peas, pulses, and soybeans²) as disaggregated individual crop data were not available. Food supply data for animal products: beef, mutton, pork, and poultry meat, along with milk and butter were also collected. Production quantity data for each of the above products (legume groups and animal products) were also collected from the FBS for the period 1961-2013 (the first and last year available in the dataset). Data was collected using the European Union aggregation from the FBS, which includes data for all EU-28 MS during the period 1961-2013.

Data of production area dedicated to each crop group (beans, peas, pulses, and soybeans) were collected from the FAO (2017) for the period 1961-2015. As part of this study we focus upon internal production markets of each product and do not consider trade data (imports/ exports). Individual crop data were collected and grouped where necessary to align with the FBS defined crop groups. Total arable area data for each MS were also collected for the same period. This allowed for a percentage of each crop group, relative to the total arable land area to be calculated. To analyse the effect of the EU's CAP, data for production area (and arable area) were collected for all EU MS for the years in which they formed part of the European Union (or within its previous naming designations). For example data for Spain was only collected from 1986-2015, with data for Italy collected from 1961-2015.

Participatory Analysis

Eames et al. (2013) suggest that engagement with stakeholders is vital when considering complex and long-term societal issues, especially when attempting to characterise desirable futures (van Berkel and Verburg, 2012). To investigate potential strategies for encouraging shifts in consumption and production of protein-rich products across the European Union a participatory methodology was adopted and developed within two stakeholder workshops. Two different but complementary participatory methods were applied in the stakeholder workshops: card technique and voting was applied in the first, and participatory backcasting in the second.

Stakeholder Workshops

The stakeholder workshops were performed during the period May 2017- February 2018. The workshops involved stakeholders from across the European Union and were performed as part of the project PROTEIN2FOOD.

Invited stakeholders either formed part of the project, or were selected due to their expertise in relation to plant-proteins in the EU. Participants represented industries and sectors throughout the production-processing-consumption chain, including: farmers associations, researchers, non-governmental organisations (NGOs), food processing companies, sales, consultants, and communication experts (Table 5).

² Classified by the FAO as: beans (beans, dry); peas (peas, dry); pulses (broad beans dry, chick peas, cow peas, pigeon peas, lentils, bambara beans, vetches, lupins, and pulses nested), soybeans (soybeans).

Table 5. Stakeholder workshops

Date and Location	Group	No of Participants	Countries Represented	Stakeholder Groups Represented	Methodology
May 30 th 2017	1	6	Italy	NGO, farmers association, food processor, farmers, and machinery manufacturer	Card technique and voting
Caserta (Italy)	2	6	France, Spain, Morocco	Researchers, farmers, and food processing companies	
March 2 nd 2018	1	19	Denmark, France, Germany, Ireland, Italy, Netherlands, Spain, Sweden, Romania, UK	Researchers, raw product producers, agricultural consultants, raw product traders, product transformation and development industry, final product industry, NGO	Backcasting technique
Freising (Germany)	2	18	Belgium, Denmark, France, Germany, Ireland, Italy, Netherlands, Poland, Spain, UK	Researchers, raw product producers, product marketing, product transformation and development industry, nutrition communication consultants	

Workshop 1

Workshop 1 was performed on May 30th 2017 in Caserta (Italy). Participants consisted entirely of non-PROTEIN2FOOD affiliated stakeholders. Stakeholders were invited from 4 Mediterranean countries (3 MS and 1 non-EU country). Representatives from these MS (Spain, France, and Italy) were invited due to the traditional importance of these countries in terms of production and consumption of legumes within the EU.

The participants were split into two groups (split by language: English and Italian) and were invited to discuss current barriers and opportunities for plant protein production and consumption in the EU. Barriers and opportunities were identified and voted on using the card-technique. These barriers and opportunities were then incorporated within the methodology applied in Workshop 2.

Workshop 2

Workshop 2 was held on March 2nd 2018 in Freising (Germany). Participants consisted of a mix of both PROTEIN2FOOD affiliated and non-affiliated stakeholders, with a number of participants having taken part in Workshop 1. Considering the desire for EU wide changes to production and consumption of plant proteins in the future, participants were invited from across the EU, with representatives from northern, southern, central, and eastern EU MS.

Two groups (evenly and diversely split) implemented a backcasting approach to discuss potential strategies for achieving a future shift in consumption and production of plant and animal proteins in the EU. As part of the second workshop results from the first workshop were presented to participants to ensure continuity. Following Kok et al. (2011), a comparative

analysis of the backcasting exercises, performed by each of the groups, was carried out to identify robust strategies across the backcasts.

Both workshops were facilitated by facilitators with a long experience of implementing stakeholder based interactions (e.g. Varela-Ortega et al., 2016; Esteve et al., 2018).

Participatory techniques

Card Technique and Voting

The card technique allows for elicitation of stakeholders' perspectives on a given question, through dialogue development and voting. It has been widely implemented as a pre-cursor to more complex participatory approaches (e.g. Ziv et al., 2018). This technique invites participants to write down a certain number of factors, which they feel are key in relation to a given subject, and then vote on which of these factors is the most important.

The card technique applied in this study consists of four steps:

Step 1: Brainstorming

In a plenary session, participants were presented with the results from the past trends analysis. This presentation was given to situate and inform stakeholders of the past situation of plant-proteins in the EU and to initiate discussions on past and future market trends. Following this introduction, participants were asked to consider and discuss the current situation for plant proteins in the EU considering both production and consumption.

Step 2: Post-it session

Participants were split into two groups (as explained in the previous section 'Workshop 1'). They were given three cards (post-its/sticky notes) and asked to write down individually the three most relevant factors from their perspectives. Each participant was then invited to present their factors and then place them on a board amongst factors suggested by other participants. Similar factors were grouped together by participants, with assistance from the facilitators. This was repeated twice, with stakeholders identifying the most relevant barriers and opportunities.

Step 3: Voting and Ranking

Following a brief discussion of the outcomes from the previous step, stakeholders were then given the opportunity to vote upon which of the factors was most important. This was repeated for both barriers and opportunities.

Step 4: Plenary Discussion

Following the previous three steps, the two groups were brought back together (to the plenary). A representative from each group then presented the barriers and opportunities identified during the exercise to the other group (and vice versa). This was followed by a general discussion of the results.

Backcasting Technique

Backcasting explores future desirable end-points, which may be distinct from predicted futures (Robinson, 1982), to assist in planning and decision-making (Dreborg, 2004). Backcasting presents the opportunity to explore the desirability and feasibility of alternative future conditions and formulate solutions for their achievement (Kok et al., 2011). Backcasting has been widely implemented including stakeholder knowledge for planning processes (e.g. Kok et al., 2011). In participatory backcasting, stakeholders work backwards from an agreed end-point, defining milestones and describing actions required for the achievement of the goal (Salter et al., 2010). Van Vliet (2011) suggests that performing backcasting with stakeholders can liberate them of constraints in present thinking and offer greater freedom in the development of more creative solutions. Stakeholder engagement can also expand the knowledge base and provide an opportunity for social learning (Swart et al., 2004), increase legitimisation of outputs (van de Kerkhof, 2006), and allow for consensus building (Nassauer and Corry, 2004).

The implementation of the backcasting technique was split into the following six steps:

Step 1: Definition of Desired Objectives

A desirable end-point was presented based upon the expected impacts of the project PROTEIN2FOOD: to increase the EU's arable land destined for protein-crop production and accelerate the EU's transition in consumption from animal-based to plant-based proteins. This was then discussed, refined and agreed upon, following input from workshop participants during a plenary at the start of the workshop.

The desired end-point in 2030 was agreed as *"To increase plant-protein: production by 25% and consumption by 10%"*. The year 2030 was selected due to the timeline and expected impacts of the PROTEIN2FOOD project, its temporal proximity to facilitate participants' ability to imagine a future, and to coincide with the targets of relevant international initiatives, such as the Sustainable Development Goals and one of the EU's key research and innovation policy response: FOOD 2030. FOOD 2030 will investigate actions required to *"...transform and future-proof [EU] food systems to be sustainable..."* and includes the PROTEIN2FOOD project as a relevant research and innovation achievement under its first priority 'Nutrition for sustainable and healthy diets' (European Commission, 2016).

Following the agreement of the objective during the introduction, the group was split into two evenly distributed group (as explained in the previous section 'Workshop 2') where steps two to five were performed identically as two individual groups, and step six with the group as a whole. As part of steps two to four, the card-technique was utilised, with voting used only in step four.

Step 2: Defining Milestones

Milestones were defined as interim objectives that need to be reached to achieve the agreed upon desirable objective. As part of this step, participants were each given a yellow card and invited to suggest one milestone, necessary for achieving the objective. Each participant was asked to explain the milestone to other participants and place it on the backcasting timeline (2015-2030). Participants were also asked to consider why the milestones are needed, what they

entail, and when they need to be achieved. Similar milestones were clustered by participants, with assistance from the facilitators, if they appeared at similar points along the timeline.

Step 3: Identifying Barriers and Opportunities

In this step, barriers and opportunities for achieving the objective and the milestones were identified. Stakeholders were given the opportunity to present factors or processes that they considered to stand in the way of the desired end-point. Similarly, opportunities that can be taken advantage of to achieve the objective and the interim milestones were provided by stakeholders. As with the milestones, each participant was given a card (red for barriers and green for opportunities) and asked to explain the barrier/ opportunity to the other participants and then to place it on the backcasting timeline. Barriers and opportunities from the first workshop were initially presented to participants and could be re-used and placed upon the backcast timeline if desired. Barriers and opportunities were clustered together if they appeared at temporally similar points along the timeline.

Step 4: Identifying Policy Actions

Participants were then asked to identify policy actions that could be implemented to achieve the objective and milestones, address the barriers, or take advantage of the opportunities. Participants were requested to be as specific as possible, specifying what these actions would entail, who would enforce them, and when they would be implemented. As with the previous two steps, the card-technique was used with participants given a blue card and invited to describe the action and place it upon the backcast timeline. As part of this step voting was also used. Individual participants were then invited to vote upon which of the policy actions is most needed to achieve the final objective. Participants gave three votes to the most important, two votes to second, and one to the third.

Step 5: Defining Strategies

Participants were then asked to develop pathways from the objective (2030) back to the present (2015) connecting milestones and necessary policy actions required for their achievement and considerate of the timeline.

Step 6: Identifying Robust Strategies

Following the previous five steps, the two groups returned to one group for a plenary discussion. Each group presented their backcasting, with a comparison made of the two backcasts by participants. In particular, the discussion focussed upon the strategies outlined by both groups, with similarities between these strategies highlighted. From this discussion and comparison, a series of robust strategies were identified and policy suggestions derived.

2.7 Addressing Climate Change: Biophysical Climate based Crop Modelling

As a means of measuring the potential for meat replacement products in Europe under future climate, a crop suitability analysis was applied at a national scale. Further, it was also developed to outline potential replacement crop possibilities and portfolios under climate change across all regions of Europe (at 4 km² scale).

Crops and Area

This analysis examines the suitability of 13 protein-rich legume and pseudo-cereal crops (Table 6) across EU-28 countries under contemporary and future (2050) climates. These crops were selected due to their historic presence in European agriculture, their importance for human food and animal feed, and their presence in agronomic testing (De Ron, 2015). Crop suitability was analysed at NUTS (Nomenclature of Territorial Units of Statistics) 1 and 2 levels for all EU-28 MS, with the exception of Malta, excluded due to its small agricultural area. The analysis was performed only in areas currently recognised as cropland (Ramankutty et al., 2008). Future cropland area is assumed to be stable, despite demonstrations of potential future shifts (Porifirio et al., 2017).

Table 6. List of legume and pseudo-cereals analysed.

Common Name	Scientific Name	Crop Type
Amaranth	(<i>Amaranthus spp.</i>)	Pseudo-cereal
Andean lupin	(<i>Lupinus mutabilis</i>)	Legume
Blue lupin	(<i>Lupinus angustifolius</i>)	Legume
Buckwheat	(<i>Fagopyrum esculentum</i>)	Pseudo-cereal
Chickpea	(<i>Cicer arietinum</i>)	Legume
Common bean	(<i>Phaseolus vulgaris</i>)	Legume
Cow pea	(<i>Vigna unguiculata ssp. unguiculata</i>)	Legume
Faba bean	(<i>Vicia faba</i>)	Legume
Lentil	(<i>Lens culinaris</i>)	Legume
Pea	(<i>Pisum sativum</i>)	Legume
Quinoa	(<i>Chenopodium quinoa</i>)	Pseudo-cereal
Soybean	(<i>Glycine max</i>)	Legume
White lupin	(<i>Lupinus albus</i>)	Legume

EcoCrop and Extension

EcoCrop (Hijmans and Elith, 2017) from the *dismo* package of R assesses the suitability of an environment for cultivation of a specified crop. EcoCrop has been widely applied (Ramirez-Villegas et al., 2013; Piikki et al., 2017), with Vermeulen et al. (2013) demonstrating that its outputs are largely consistent with those of more complex models. Notwithstanding its limitations (Ramirez-Villegas et al., 2013), EcoCrop represents an appropriate tool for developing a coarse understanding of the impacts of climate change on protein-rich crop suitability in Europe in 2050.

EcoCrop compares monthly precipitation and temperature data with environmental niche ranges required for crop growth (FAO, 2016b). EcoCrop tests 12 potential growing seasons, calculating an independent suitability value for both temperature and precipitation. As part of this, it also assesses whether required conditions persist long enough during each season to permit the crop to go through its normal growth cycle. The temperature and precipitation

suitability values for each growing season are then multiplied, with the maximum value from the 12 potential growing seasons considered the suitability index for the crop. Suitability ranges from 0 (unsuitable) to 1 (suitable).

For each growing season_{*i*}, EcoCrop calculates whether temperature ranges in a given land surface pixel are firstly permissible ($T_{min}T_{max}$) for growth, and secondly whether they are within an optimal growth range ($T_{opmin}T_{opmax}$). If the mean temperature ($\bar{T}_i$) of the evaluated growing season is within the optimal temperature range, as defined by the crop parameters (FAO, 2016b), this results in a temperature suitability value of 1. If however, the mean temperature falls outside of the optimal range, but within the permissible range temperature suitability is set at more than zero and less than one. If the mean temperature of the growing season falls between T_{min} and T_{opmin} suitability is calculated as shown in equation 16, whilst if it falls between T_{opmax} and T_{max} it is calculated as shown in equation 17. If the mean temperature falls outside of the permissible temperature range ($T_{min}T_{max}$) suitability is set to 0.

$$TSuit_i = \frac{\bar{T}_i - T_{min}}{T_{opmin} - T_{min}} \quad 16$$

$$TSuit_i = \frac{T_{max} - \bar{T}_i}{T_{max} - T_{opmax}} \quad 17$$

EcoCrop also evaluates minimum temperature values, using a death temperature (T_{kill}), derived from FAO (2016b). If within the growing season the minimum temperature drops to $T_{kill} + 4^\circ\text{C}$, temperature suitability is set to 0. Using each month as the potential start of growing season_{*i*}, EcoCrop analyses the temperature data for the months that fall within this cycle. The geometric mean of the crop cycle, defined by the EcoCrop database (FAO, 2016b) was used for crop cycle length.

EcoCrop then evaluates the precipitation suitability for growing season_{*i*} by calculating the cumulative precipitation (P_i) over the length of the crop cycle, including one month before and one month after the season. As with the temperature suitability, EcoCrop assesses whether these cumulative precipitation values lie within a permissible range of required cumulative precipitation ($P_{min}P_{max}$), or within the optimal range ($P_{opmin}P_{opmax}$) for this crop, as defined by FAO (2016b). If precipitation is within the optimal cumulative range, this results in a precipitation suitability value of 1. If cumulative precipitation falls outside of this, but within the permissible range precipitation suitability is set at more than zero and less than one. If the cumulative precipitation falls between P_{min} and P_{opmin} suitability is calculated as shown in equation 18, whilst if it falls between P_{opmax} and P_{max} it is calculated as shown in equation 19. If cumulative precipitation falls outside of the permissible range ($P_{min}P_{max}$) suitability is set to 0.

$$PSuit_i = \frac{P_i - P_{min}}{P_{opmin} - P_{min}} \quad 18$$

$$PSuit_i = \frac{P_{max} - P_i}{P_{max} - P_{opmax}} \quad 19$$

Following the development of the 12 $TSuit_i$ and $PSuit_i$ values, these are then multiplied to develop 12 growing season suitability values ($Suit_i$) (equation 20). From this series, EcoCrop takes the highest value as the crop suitability value ($Suit$), based upon the assumption that a farmer plants during this ideal period.

$$Suit = \max[Suit_i = (TSuit_i * PSuit_i)] \quad 20$$

EcoCrop is highly flexible and permits the inclusion of extra parameters to further refine crop suitability, as demonstrated by Pikki et al. (2017). As an extension to the original EcoCrop model, a parameter for soil pH is included. Soil pH was selected due to its observed effects upon water uptake, nutrient availability, and crop growth (Kemmitt et al., 2006; Ghimire et al., 2017). Other soil parameters were also considered, but were omitted due to a lack of consistent data and niche range values. Soil pH has been shown to fluctuate daily and seasonally due to precipitation and may also change in the future due to climate change (Rengel, 2002; Rengel, 2011). Despite these observations, soil pH was considered a constant due to a lack of contemporary and future monthly pH data. As pH was assumed to be constant, pH suitability was only calculated once, rather than for the 12 aforementioned growing seasons.

The calculation of $pHSuit$ was identical to that of temperature and equations 16 and 17, with a permissible soil pH range ($pH_{min}pH_{max}$) and an optimal range ($pH_{opmin}pH_{opmax}$) developed, as defined by FAO (2016b). If the pH value lies within the optimal pH range, pH suitability was set to 1. If however, the pH value falls outside of the optimal range, but within the permissible range pH suitability is set at more than zero and less than one. If the pH falls between ($pH_{min}pH_{max}$) suitability is calculated as shown in equation 16, whilst if it falls between ($pH_{opmin}pH_{opmax}$) it is calculated as in equation 17.

Following the calculation of $pHSuit$, crop suitability was assumed to be limited by the minimum value of climatic suitability ($TSuit * PSuit$) and soil suitability $pHSuit$. Crop suitability, under the extended model, for each cropland pixel was defined as being the minimum value from the climatic and soil suitability values, as defined in equation 21. The smallest value from this equation was assumed to represent the parameter that limited crop suitability and was extracted during analysis.

$$Suit = \min[(TSuit * PSuit); pHSuit] \quad 21$$

The EcoCrop model (and extension) were both run using current climate data to develop a contemporary baseline, and were also run using climate data for each of the 30 GCMs, under RCP4.5.

Crop, Climate, and Soil Data

Crop suitability was modelled using climate and soil data for present and future conditions. These data were analysed subject to expert derived crop-specific admissible ranges, with parameter data extracted from the EcoCrop database maintained by the FAO (2016b). An assumption was made that no crop breeding programmes are performed that would alter these parameter ranges.

Current climate data were sourced from WorldClim, which contains average monthly climate data for temperature (minimum, maximum, and mean) and precipitation for the period 1970-2000 (Fick and Hijmans, 2017). From WorldClim, 12 monthly data sets of precipitation, minimum, and mean temperature data were collected to analyse present suitability, at a resolution of 2.5 arc minutes ($\sim 4.5 \text{ km}^2$ at the equator). Future climate data (2050s) were taken from the Climate Change, Agriculture and Food Security (CCAFS) database (<http://ccafs-climate.org/data/>). These data had been previously downscaled, as described by Ramirez and Jarvis (2010). 12 monthly data sets were collected for precipitation, minimum and mean temperatures at a resolution of 2.5 arc minutes. Data were collected for the 30 available Global Circulation Models (GCMs) (Annex 4: List of the 30 Global Circulation Models used within the analysis) under Representative Concentration Pathway (RCP) 4.5. RCP4.5 was selected as the scenario behind this pathway (IPCC, 2014) as it was considered the most probable and informative for 2050.

Soil pH data were sourced from the International Soil Reference and Information Centre (ISRIC) and their SoilGrids platform (www.soilgrids.org). Data were collected at depths of 0, 5, 15, and 30cm at 30 arc seconds, with average pH values (0-30cm) calculated using the software *R*. Soil data were aggregated to 2.5 arc minutes, and cropped to correspond with the climate data.

All data were cropped to 75°N-30°S and 55°E- -15°W, incorporating all EU-28 MS.

Current Distribution Analysis

To analyse current protein-rich crop distributions and their potential relationship with climate suitability, EcoCrop suitability outputs were evaluated against sub-national (NUTS-2) agricultural production statistics (European Commission, 2017). This analysis was performed for all crops with available and disaggregated sub-national data. Suitability is only one of the limiting factors in crop selection, so an asymmetric relationship between production and suitability is expected. Crops can be absent in highly suitable areas, but are not expected to be present in highly unsuitable areas. To analyse this type of relationship quantile regressions focusing on the highest quantile (95th) of production were performed.

Production area data were sourced for the year 2010 for blue lupin, buckwheat, faba bean, pea, and soybean. The proportional distribution of each crop, in all NUTS-2 regions, was calculated from the total production of all protein-rich crops within that region. For each NUTS-2 region and crop combination, from EcoCrop outputs for the maximum and mean suitability values of

the pixels falling in that region were derived. In performing the suitability analysis EcoCrop was implemented under the assumption that rainfall was not an absolute limiting factor, to allow for the possibility of irrigated production.

Future Suitability Analysis

To identify how climate change may affect suitability across EU-28 MS, percentage changes in aggregated national suitability were calculated from EcoCrop outputs under the baseline and future climates. For both baseline and future suitability, the minimum suitability value (climatic or soil) was used to define the limiting factor for each cropland area pixel. Modal values for limiting factors were calculated for each crop in each country. Aggregated national suitability was defined from the average of suitability values for all cropland surface pixels within national boundaries (Ramankutty et al., 2008). This calculation was replicated for all the 30 GCMs runs of the model.

Ideal baseline and future crop options for each cropland surface pixel were also identified. The baseline ideal crop option was developed from stacking all crop suitability layers. From this stack, the maximum suitability value from within the stack for each surface pixel was extracted, with this maximum value corresponding to a crop layer. A layer with the highest suitability values (across all crops) for each surface pixel was developed and was used to define ideal crop options. In defining future ideal crop options, a similar approach was applied. However, a crop suitability layer that included results from all 30 GCMs was initially developed. For this, the maximum suitability value for each cropland surface pixel was extracted from the stack of 30 GCM specific crop layers. This was repeated for each crop. These maximum suitability layers were then stacked. Using these maximum crop suitability layers, the same methodology as for the current ideal option was repeated.

For the future analyses rainfed crop production was assumed. Irrigation in Europe is not expected to expand greatly in the future (Alexandratos and Bruinsma, 2012), which implies that expansion of the analysed crops will likely be into non-irrigated areas. Also, the crops are analysed within the context of their potential as meat replacements in order to reduce environmental impacts. Therefore, identification of production areas was focused on areas where the crops are not competing strongly for scarce water resources.

Sensitivity Analysis

To test the robustness of this analysis, the sensitivity of the EcoCrop outputs to changes in parameters within the model was analysed. Previous analyses of EcoCrop (e.g. Ramirez-Villegas et al., 2013; Manners and van Etten, 2018) have highlighted the robustness of the model and the limited sensitivity of parameter changes. Despite this, sensitivity of EcoCrop outputs to changes in temperature, precipitation, pH, and crop cycle length were investigated.

Parameter ranges defined by FAO (2012) were altered, to vary them to such an extent that the correct parameter value is likely to be found within that range. Following Manners and van Etten

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(2018), changes were made to the maximum and minimum temperature parameters by $\pm 2^{\circ}\text{C}$, alterations were made to the range of precipitation by $\pm 25\%$, variations to the permissible range of pH values by $\pm 25\%$, and the crop cycle length was changed by ± 30 days ($\pm 1\text{m}$). Changes to crop cycle length were combined with the other three parameters, to observe potential interactions. Sixteen tests of sensitivity were performed (Table 7).

Table 7. Sensitivity scenarios representing crop parameter changes.

Change in temperature, precipitation, or soil pH	Crop Cycle +1 Month	Crop Cycle -1 Month
Minimum temperature $+2^{\circ}\text{C}$	<i>Tmin+2C+1m</i>	<i>Tmin+2C-1m</i>
Minimum temperature -2°C	<i>Tmin-2C+1m</i>	<i>Tmin-2C-1m</i>
Maximum temperature $+2^{\circ}\text{C}$	<i>Tmax+2C+1m</i>	<i>Tmax+2C-1m</i>
Maximum temperature -2°C	<i>Tmax-2C+1m</i>	<i>Tmax-2C-1m</i>
Precipitation $+25\%$	<i>Pre+25%+1m</i>	<i>Pre+25%-1m</i>
Precipitation -25%	<i>Pre-25%+1m</i>	<i>Pre-25%-1m</i>
pH $+25\%$	<i>pH+25%+1m</i>	<i>pH+25%-1m</i>
pH -25%	<i>pH-25%+1m</i>	<i>pH-25%-1m</i>

Suitability sensitivity was estimated using average EcoCrop outputs for each crop in each EU-28 country, under the conditions of sensitivity tests, compared to baseline results. Baseline results were developed using FAO (2012) parameter data. As with Manners and van Etten (2018), changes in suitability were simply categorised as increase, decrease, or remain the same.

3. RESULTS

The results from the application of this multi-disciplinary analysis of land use change, with specific focus upon forest vulnerability to socio-economic factors, trade-offs between agricultural activities and ecosystem services conservation, the current trends of global consumption changes, and how future climate might affect the options for potential animal product replacements are presented below.

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

Results of Indicator Weighting

In developing the index of forest vulnerability to deforestation from socio-economic development, the first results derived were from the development of weights for each of the 13 identified indicators of vulnerability. All indicator weights were developed from expert interviews and stakeholder interactions. Outcomes from the survey performed with over 20 experts from the ROBIN project (Table 8) identified that governance indicators, agricultural growth, and road density as the most influential indicators in driving deforestation. Stakeholders were found to perceive largely similar conditions, where governance indicators and agricultural area growth are the most important indicators within each of the three respective state case studies.

Table 8. Results from expert survey and stakeholder workshops for Deforestation Vulnerability Index (DVI) weighting.

Indicator	Expert Weight	Stakeholder weights		
		Bolivia	Brazil	Mexico
GDP per Capita (PPP)	0.08	0.00	0.01	0.01
Growth in Agriculture Value	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

Note: 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.

The National Index

The Deforestation Vulnerability Index under expert weighing (Figure 10) suggests relative stability of vulnerability across most LAC countries from 2000-2010. Despite this, 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 10b), where more than 80% of countries saw vulnerability increase, before declining again (Figure 10c). The percentage change in vulnerability during the period 2000-2010 is shown in Figure 10d. This demonstrates that vulnerability reduced marginally in Amazonian countries including in Bolivia (-4%) and Brazil (-6%). It also highlights the difference in vulnerability change in neighbouring countries with Chile (-44%) and Argentina (+29%) found to be on the extremes of vulnerability change during the analysed period. Tabulated national results shown in Annex 5.

Figure 10. Deforestation Vulnerability Index (DVI) results for Latin American and Caribbean.

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Note: a) DVI outputs for the year 2000. b) DVI outputs for the year 2005. c) DVI outputs for the year 2010. d) Percentage change in DVI outputs from 2000-2010.

To tease out the source of identified changes to vulnerability (Figure 10), Figure 11 presents the weighted vulnerability values for each of the 13 DVI indicators. The results for 2000 (Figure 11a) 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 11b), the continental wide increase in vulnerability is observed, and can be sourced to agricultural area growth (with changes in Honduras being particularly great), along with changes to the governance indicators, specifically regulatory quality.

Figure 11. Weighted vulnerability values for the Deforestation Vulnerability Index (DVI) indicators.

Note: Developed 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.

The tail of the vulnerability spike can be seen in Figure 11c, with agricultural area growth lower than in both 2000 and 2005 (exceptions include Suriname), coupled with simultaneous reductions in vulnerability from governance indicators.

The State Index

The results of the state DVI are shown in Figure 12, where in each state vulnerability under both weighting schemes was higher than the national results. Despite states being in many cases within the same vulnerability category as the national results, the actual DVI values were distinct. Application of the stakeholder weight (Figure 12b) results in a notable increase in vulnerability compared with the expert weight (Figure 12a). In Bolivia, application of the stakeholder weight increased vulnerability by two categories compared to the expert weight, 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. Tabulated state results under both weighting schemes available in Annex 6.

Under expert weighting (Figure 12a) each state was found to be at least 15% more vulnerable than the national value. Whereas, under stakeholder weighting (Figure 12b) 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 Figure 10 and Figure 12 differ slightly due to use of different GDP data (see Methodology).

Figure 12. State Deforestation Vulnerability Index (DVI) values for the year 2010.

Note: Results presented are for analysed states (Pará, Santa Cruz, and Jalisco) and their respective countries, under the conditions and data of the state index. National results developed using national data for state index indicators. DVI indicator values were normalised using all 24 countries' and 3 states' data to reduce exaggerated results. Only analysed states and their respective countries are presented as stakeholder weighting could not be generated for all 24 countries. a) DVI for selected state examples and their respective countries under expert weighting. b) DVI for selected state examples and their respective countries under stakeholder weighting.

Sources of vulnerability in the state index are shown in Figure 13, under expert weighting (Figure 13a) and stakeholder weighting (Figure 13b). Under expert weighting, vulnerability across the states 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 11, vulnerability can also be attributed to poor governance factors with political stability especially important in Mexico (and Jalisco), whilst regulatory quality contributes to forest vulnerability in Bolivia (and Santa Cruz). In contrast, the results from the stakeholder weighting (Figure 13b) highlight that vulnerability concentrates in governmental effectiveness and regulatory quality for all countries and states, with agricultural area growth to a lesser extent also an important contributor.

Figure 13. Weighted vulnerability values for provincial Deforestation Vulnerability Index (DVI) indicators.

Note: a) Indicator vulnerability under expert weighting. b) Indicator vulnerability under stakeholder weighting.

Robustness and Sensitivity of National DVI

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 14). 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 for all countries.

Figure 14. Estimation of the sensitivity of the Deforestation Vulnerability Index (DVI) in LAC.

Note: Developed using random weights from 1000 Monte Carlo tests for the year 2010. Overlaid blue dots represent national DVI results under expert weighting. Median values explained by horizontal line within box, 25%-75% quartiles demonstrated by upper and lower box lines, and maximum and minimum vales by box whiskers.

An analysis of variance (ANOVA) on the results from Figure 14 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 Annex 7: Results from pairwise t-test analysis of DVI under random weighting). 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.

3.2 The role of decision making in ecosystem service trade-offs in Amazonian agricultural-forest systems

Conflict Among Goals

To determine the relationship between the two goals analysed (net farm income and net carbon sequestration) a payoff matrix was calculated for each representative farm. The values within the payoff matrix were developed from maximising both goals (equations 4 and 5) separately for each farm type, subject to equations 6-12, under the conditions of the baseline. Table 9 displays the results from these calculations. The values in the third column show the results when net farm income is maximised, the fourth column the results when net farm carbon sequestration is maximised. The best possible values (ideal value) for each goal are displayed in bold and the anti-ideal value in italics. Ideal values represent satisficing values for each farm.

Table 9. Payoff matrix for all farm types

Farm Type	Goal	<i>Max:</i> Net Farm Income	<i>Max:</i> Farm Carbon Sequestration
Small	Net Farm Income (1000 USD)	22.9	<i>8.7</i>
	Net Farm Carbon Sequestration (1000t CO ₂ eq)	<i>-0.8</i>	0.05
Large	Net Farm Income (1000 USD)	147.1	<i>74.6</i>
	Net Farm Carbon Sequestration (1000t CO ₂ eq)	<i>-2.1</i>	0.05
Very Large	Net Farm Income (1000 USD)	264	<i>194.3</i>
	Net Farm Carbon Sequestration (1000t CO ₂ eq)	<i>-2.3</i>	0.11

Values in bold are ideal values, italic values are anti-ideal

The outputs displayed demonstrate an antagonistic relationship between the goals, repeated across all farm types. Inspection of Table 9 shows that on the small farm maximisation of net farm income results in income of 22.9 (1000 USD), with farm carbon sequestration of -768 tonnes. In contrast, maximising sequestration results in 48 tonnes of carbon sequestration, 1591% more than the anti-ideal value, and 8.7 (1000 USD) of income (62% less than the ideal value). A similar pattern is seen on the large farm where maximisation of income results in 147.1 (1000 USD) of income and -2093 tonnes of sequestered carbon. Maximising sequestration results in 46 tonnes (2217% more than anti-ideal value) and 75 (1000 USD) (49% less than ideal value). Finally, on the very large farm maximising sequestration results in 107 tonnes of carbon sequestered and 194 (1000 USD) of farm income. Maximisation of income results in 264 (1000 USD) (36% more than anti-ideal value) and -2341 tonnes of sequestered carbon (2196% less than ideal value).

Impact of Decision Making in Goal Achievement

To explore the role of decision-making in achieving (or not) the satisficing values (Table 9) and the contrasting effect of this achievement on the opposing goal, Figure 15 was developed. The results outline the clear role that decision-making can have in the extent of the antagonistic nature of the relationship. Decision-makers were simulated through changes in λ , representing differences in desire for achievement of each goal, where $\lambda=1$ represents decision-making only concerned with farm income, and $\lambda=0$ with farm carbon sequestration. Figure 15 illustrates that the scale of the trade-off between farm income and farm sequestration relationship is most pronounced under the extreme management preferences, especially when $\lambda > 0.6$. It is within the moderate management preferences ($\lambda=0.4-0.6$) that the trade-offs are less pronounced, which implies at their management solution potential. The results also suggest that the policy scenarios applied are ineffective at limiting the trade-off as a whole, but they merely force the more marked impacts towards the extremes of the weighting preference scale. This suggests that there exist opportunities for policies to encourage movement towards more balanced, rather than extreme management preferences.

Figure 15. The effect of decision-making upon net farm carbon sequestration and net farm income.

Note. Results developed across three representative farm types of the Province of Guarayos under the conditions of the baseline and two policy scenarios. Full management preference for farm income ($\lambda=1$) and forest conservation ($\lambda=0$).

The effects of decision-making across the indicators used to define the goals (crop production, deforested timber, forestry product, mature forest sequestration, reforested forest sequestration, deforested land emissions, and cropped land emissions) are available in Figure 16. The results displayed present similar patterns to that of Figure 15, in terms of both the role of decision-making and the impacts of the policy scenarios.

Figure 16. The effect of decision-making upon Ecosystem Service Indicators.

Note. Results developed across three representative farm types of the Province of Guarayos under the conditions of the baseline and two policy scenarios. Full management preference for farm income ($\lambda=1$) and forest conservation ($\lambda=0$).

Identifying Satisficing Management Solutions

From Table 9 and Figure 15 it is clear that simultaneously satisfying both goals is impossible. Despite this, the outputs of the modelling did offer a series of intermediate achievement (of both goals) solutions for each farm (Table 10). In many cases, these solutions are repeated over a number of weighting schemes (Table 10-‘Solution Repetition’). The small farm was found to have the greatest number of solutions available. Viable solutions for relative achievement of each goal for each farm (and policy scenario) are found in the more moderate preference range ($\lambda=0.3-0.7$). The implementation of the policy scenarios improved income and/or sequestration in these solutions, explaining the results of Figure 15. Potential solutions on the small farm range around 14-17,000 USD of income and 10-18 tonnes of sequestration. On the large farm, viable solutions appear to range from 86-120,000 USD of income and 20-50 tonnes of sequestration. On the very large farm, the solutions are dichotomous, with only the CES scenario providing more than two solutions.

Table 10. Potential management solutions across three farm types and under policy scenario conditions.

Farm	Scenario	λ	Solution Repetition (no.)	Net Farm Income (1000 USD)	% of Goal	Net Farm Carbon Sequestration (1000 t CO ₂ eq)	% of Goal
Small	Baseline	1	1	22.9	100	-0.77	-1591
		0.9	1	14.8	65	0.01	27
		0.8	1	14.1	61	0.02	44
		0.7	1	9.9	44	0.04	95
		0.6-0.4	3	9.7	42	0.04	97
		0.3-0	4	8.8	38	0.05	100
	CES	1	1	22.9	100	-0.77	-1591
		0.9	1	16.8	74	0.03	56
		0.8	1	16.1	70	0.04	73
		0.7-0.1	7	14.1	61	0.05	99
		0	1	13.8	60	0.05	100
	SED	1	1	22.9	103	-0.72	-1488
		0.9	1	17.4	76	0.01	24
		0.8	1	17.3	75	0.01	28
		0.7	1	13.2	58	0.03	73
		0.6-0.3	4	10.3	45	0.05	97
Large	Baseline	1	1	147.1	100	-2.1	-4509
		0.9	1	86.1	59	0.02	39
		0.8-0.1	8	74.6	51	0.05	99
		0	1	74.2	50	0.05	100
	CES	1	1	147.1	100	-0.22	-470
		0.9-0.1	9	118.3	80	0.05	99
		0	1	91.7	62	0.13	275
	SED	1	1	178.5	121	-2.1	-4509
		0.9	1	103.8	71	0.02	49
		0.8-0	9	92.3	63	0.05	99
Very Large	Baseline	1	1	263.9	100	-2.3	-2196
		0.9-0	10	194.4	74	0.11	100
	CES	1	1	279.7	106	-2.1	100
		0.9-0.1	9	260.2	99	0.11	100
		0	1	238.5	90	0.34	318
	SED	1	1	391.3	148	-2.3	-2196
		0.9-0	10	281	106	0.11	100

In Figure 17, achievement frontiers of the two goals are presented (baseline and policy scenarios) for each of the representative farm types. Although the results do not replicate continuous curved achievement frontiers, they do demonstrate an inverse relationship between net farm income and net farm carbon sequestration. Across the three farms (Figure 17 ‘Small’, ‘Large’, ‘Very Large’), the potential management solutions (Table 10) are presented with points along the frontier. Under the conditions of the scenarios, the achievement frontiers move upwards across all farms. In the case of the CES scenario, moving upwards and outwards, especially pronounced on the large farm. This movement infers that the CES scenario is successful in encouraging simultaneous increases in net farm carbon sequestration and net farm income. The SED scenario in contrast only shifts the frontiers upwards signifying increased income, but without increased sequestration. The SED policy scenario was not seen to drive considerable reductions in the net farm sequestration in comparison to the baseline on any farm. These results would suggest the potential success of the application both scenarios, but especially a CES based policy scenario.

Figure 17. Achievement frontiers of the two goals.

Note: Results based upon application of the multi objective goal programming model for the three representative farms of the Province of Guarayos, Bolivia. Three frontiers represent achievement under conditions of the baseline and two scenarios, under differential weighting. Plotted weighting values represent the repeated solutions, and the weighting in which these goal solutions move along the achievement frontier.

Across all three farms, the majority of potential management solutions lie in the space where net farm carbon sequestration is positive, with the application of the two policy scenarios providing higher levels of net farm income in each case. It is only under the most extreme weighting ($\lambda=1$) in favour of net farm income that net farm sequestration is negative (emissions). This graphically demonstrates that despite potential increases in income derived from deforestation and expansion in potential cropping area, the resultant impacts upon net farm sequestration are so extreme (i.e. sequestration turns to emissions), that no deforestation occurs. The series of options that are found around the neutral scale of weighting ($\lambda=0.3-0.7$), although not achieving either goal, may represent potentially sustainable management options.

From this analysis it is evident the considerable effect that management preferences and decision making can have in (dis)encouraging net farm income and sequestration, and the large impact that such preferences can have in ES trade-offs.

3.3 Global and EU Patterns of Consumption and Production of Protein Rich Products and Development of Robust Strategies for Transitioning EU Consumption and Production Patterns

The above results have highlighted the scale of the trade-offs between agricultural expansion and forest conservation in agriculture-forest systems. To better understand how these trade-offs might develop under continued pressure to producing agricultural products to satiate increasing global demand for animal products, it is vital to understand the historical and current trends of global diets, and also provide potential pathways for encouraging production and consumption changes.

Past protein-rich product trends

Global and Continental Consumption and Production

Analysis of global historical trends of aggregated per capita legume consumption as food (Figure 18a) highlight a long-term decline from 10.9 kg/capita/year in 1962, to 8.9 kg/capita/year in 2013. Despite this decline, there have been recent nascent global upturns driven by pulse consumption. Global production of legumes, (Figure 18b) increased more than 500% (67- 351 million tonnes (MT)) from 1961-2013. During this period, production proportions changed greatly, initially split proportionally between beans, peas, pulses, and soybeans. Soybean has dominated production from the mid-1970s onwards. In 2013, soybean production (278 MT) was almost ten times that of pulses (38 MT), and more than three times greater than beans, peas, and pulses combined (72 MT).

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Figure 18. Global and continental patterns of per capita consumption and production of legume and animal (meat and milk) products.

Continental per capita consumption patterns of legumes (Figure 18c) present not only the transitions that have occurred over the past half-century, but also their complexity. Nowhere is this complexity more evident than in Asia and Africa. In the 1960s, Asian legume per capita consumption stood just shy of 15kg, by the millennium this had almost halved. In contrast, Africa saw per capita consumption almost double to over 10kg/year, with Africa presently the greatest consumer of leguminous crops. Oceania saw consumption increase by almost 500% to a peak of 5.6kg/year in 1986, before declining to less than 9kg/capita/year in 2013. Continental production values of the crops (Figure 18d) highlight the importance of the Americas and, to a lesser extent, Asia for global legume production.

Consumption of meat products (Figure 18e) shows almost linear increases across all products, doubling from 21-41kg/year. Beef consumption peaked in 1976 at 11.59kg/capita, before declining to 9.45kg/capita in 2013. Pork almost doubled to 15.7kg/capita/year from 8.3kg/capita/year, whilst poultry consumption increased from 2.9kg in 1961 to 15.2kg in 2013, with mutton reducing slightly from 1.91-1.86kg/capita/year. Production of these selected meat products (Figure 18f) show almost linear growth, increasing by almost 450% (68-302 MT), with poultry (8.9-108 MT) and pork (24-113 MT).

The more illustrative continental patterns of meat products are shown in Figure 18g and Figure 18h. Consumption patterns (Figure 18g), demonstrate that Oceania leads consumption, peaking at over 100kg/capita/year in the 1970s. The Americas saw long-term increases, whilst European consumption appears, like production, to have peaked in the 1990s. Asian consumption increased seven-fold to 29kg/capita/year, which may help to account for the halving of legume consumption during the same period. Further, Figure 18g highlights the gulf between consumption patterns across richer and poorer continents, with Asia in a long-term march towards wealthier consumption patterns. The greatest increase in aggregated meat production (Figure 18h) was seen in Asia, increasing linearly from the 1980s onwards, suggesting a production response to the 700% increase in consumption. The Americas followed a less steep, but equally long-term increase from the 1990s onwards. European production peaked in the early 1990s, and has since stabilised.

Global milk and butter per capita consumption (Figure 18i) reduced to 88 and 0.7kg/capita/year respectively, whilst production (Figure 18j) almost doubled for both products to 635 and 9 MT. Continental consumption (Figure 18k) demonstrates that Europe, Oceania, and the Americas are the greatest dairy consumers. European consumption however declined from a peak in 1989 of 240kg/capita to 219kg/capita in 2013, with consumption in Oceania and the Americas settling around 166kg/capita/year, dwarfing that of Africa (39kg/capita/year) and Asia (61kg/capita/year). In terms of continental production (Figure 18l), Europe was found to historically dominate, with both Asia, and the Americas converging to European values, before Asia became the biggest dairy producer in the early 2000s.

From this brief analysis, a number of points should be reiterated. Firstly, global and continental animal and legume production and consumption trends are following divergent trajectories. In most cases, consumption of animal products is increasing, whilst decreasing for legumes-

reinforcing the consumption transitions towards animal product consumption. However, the downward pattern in plant protein consumption appears to have reversed globally and across many continents during the past 15 years, which may infer an inchoate reversal of long-term consumption declines. Secondly, the differences in scale of consumption are large, and continue to widen, with global consumption of animal products in 2013 being 15 times that of legumes, compared to only 9 times in 1961. Thirdly, global consumers appear to be shifting meat consumption patterns, moving away from beef, to pork and poultry.

Consumption and Production in the EU

The EU's per capita legume consumption (Figure 19a) peaked at just 3.9kg/capita/year in 1963, before reducing to the contemporary rate of 2.9kg/capita/year. This value of 2.9 kg/capita/year represents a decline of ~15% in comparison to 1961. The distribution of consumption across the legume groups was observed to have changed during the study period, especially considering the slow introduction of soybeans to EU consumption patterns. In 1961, beans were the most consumed legume group (1.4 kg/capita/year), but saw consumption almost halve to 0.78 kg/capita/year. Pulse (broad beans dry, chick peas, cow peas, pigeon peas, lentils, bambara beans, vetches, lupins, and pulses nested) consumption increased 4% to 1.04 kg/capita/year, with pea consumption remaining relatively constant at 0.92 kg/capita/year. In 2013, peas, beans, and pulses all contributed roughly 0.9 kg/capita/year per group to EU-28 consumption, with soybean around 0.2 kg/capita/year.

Figure 19. EU per capita consumption (kg/capita/year) and aggregated production (Million tonnes) of legume and animal products from 1961-2013.

In contrast, variations in total production of legumes have been far more pronounced. Production of legumes (Figure 19b) declined to the 1980s, before an exponential increase in pea and soybean production in the mid-1980s quadrupled production to almost 10 MT (million tonnes) in the space of 5 years. This peak was followed by a much less precipitous decline to less than 4 MT in 2013, due to declines in pea and to a lesser extent soybean. This rate of aggregated decline was augmented by a post millennium increase in pulse production.

EU meat consumption (Figure 19c) increased by ~50% from 1961 to the early 1990s before stabilising at ~78kg/capita/year in 2013. Beef consumption declined a third from the 1980s to 14kg/capita/year, mutton declined by a similar figure. Pork consumption increased from 24-40kg/capita/year. Poultry followed a divergent pattern, quadrupling to 22.5kg/capita/year, explaining the relative stability in aggregate EU meat consumption.

Aggregated meat production (Figure 19d) saw linear increases from the 1960s to the 1980s, before appearing to stabilise at just over 40 MT. Beef production declined to 7.5 MT, following a peak of 10 million in 1991. Pork production more than doubled to 22 MT. Poultry production increased from 1.8 MT to 12.7 MT. These values demonstrate the comparative insignificance of legume production, constituting less than a quarter of meat production, even at their production peak (~1985). In 2013, EU-28 total legume production (4.2 MT), not solely for human consumption, represented less than 10% of meat production (44 MT).

Dairy product consumption (Figure 19e) was relatively stable, with milk consumption fluctuating around 230-240kg/capita/year since the millennium, representing a ~30% increase since 1961. Butter reduced to 3.73kg/year in 2013. Milk production (Figure 19f) increased from 125-157MT, with butter declining by 10% to 1.91MT.

Legume cultivation response to the Common Agricultural Policy

The number of Common Agricultural Policy (CAP) reforms and the minutiae of how these reforms affected all legumes in each Member state, is beyond the scope of this investigation. A brief overview of potential historical CAP impacts on legumes throughout its reforms is provided.

The increases in legume production displayed in Figure 19b are reflected in Figure 20, where the proportional area of EU (countries that constituted the EU at the time) arable land dedicated to legumes jumped from roughly 1% in 1980, to over 3% in 1986. In 1982, the European Economic Community (EEC) introduced a series of deficiency payments to support pea, faba bean, and lupin production for human consumption, following previous similar payments for livestock consumption (European Parliament, 2013). Although attributing any particular agricultural policy reform to a particular trend is difficult, the response of peas to the introduction of this payment is suggestive of its positive effect across the EU (Figure 20).

Figure 20. Proportion of arable land dedicated to legumes in countries within the 'European Union' (throughout steps of accession). Common Agricultural Policy reforms overlaid.

As part of the 1992 MacSharry Reform, price supports were replaced with area-related direct payments for protein crops, cereals and oilseed crops, which were increased in subsequent years (European Parliament, 2013). Payments for pea were higher than for other crops, which may explain the continued production of peas as a European aggregate. During this period, soya received far lower payments due to restrictions on supports for oilseeds following agreements made between the European Union and the United States, as part of the Blair House Agreement (Zander et al., 2017).

Decoupling and the introduction of the protein premium as part of the 2003 CAP reform (European Parliament, 2013) appears to have had a positive effect upon pulses. The Health Check provided a number of options for individual MS for protein crops. The introduction of these measures appears to coincide with increases in pulse and pea and production from 2008 onwards. Increased soya production during this period may also be attributable to the removal of restrictions from the Blair House Agreement, although the absence of import levies on oilseed and proteins remained. However, the Health Check also agreed the removal of the aforementioned protein premium coupled payment (introduced in 2003) by the year 2011 (2012 in several states) (European Parliament, 2013). This removal may be connected with the subtle reductions in these crops (especially peas) after 2011.

EU-28 Patterns of Change

Recent spatial patterns of consumption and production of protein-rich products across EU MS from 1993-2013 are presented in Figure 21. This figure places EU-28 countries, and an EU-28 average, within four quadrants according to relative changes (from 1993-2013) in per capita consumption (Figure 21a) and production (Figure 21b) of both product groups.

The lower right quadrants of Figure 21 represent increases in consumption/ production of legumes and simultaneous reductions in animal products. These quadrants represent the idealised location for EU-28 MS considering the environmental and health benefits of consumption and production shifts away from animal to legume products.

Figure 21. Percentage changes in European Union legume and animal products consumption and production during the years 1993-1997 and 2009-2013.

Note: a) Change in consumption of legume and animal products. b) Change in production of legumes and animal products. AT: Austria, BG: Bulgaria, BLX: Belgium-Luxembourg, CY: Cyprus, CZ: Czechia, DK: Denmark, DE: Germany, EE: Estonia, EL: Greece, ES: Spain, FI: Finland, FR: France, HR: Croatia, HU: Hungary, IE: Ireland, IT: Italy, LV: Latvia, LT: Lithuania, MT: Malta, NL: Netherlands, PL: Poland, PT: Portugal, RO: Romania, SI: Slovenia, SK: Slovakia, SE: Sweden, UK: United Kingdom, and EU-28: European Union Average.

Consumption patterns (Figure 21a) show that MS cluster in the left hand quadrants (reduced legume per capita consumption). Only three countries are located in the desired, or idealised quadrant (lower right): Austria, Czechia, and Hungary. Denmark, Estonia, Romania, and Sweden were found to be increasing both legume and animal product consumption.

Production patterns (Figure 21b) largely mirror those of consumption, with MS largely not located in the desirable quadrant. Only a handful of smaller agricultural nations (Estonia, Greece, Lithuania, and Latvia) found in the most desirable quadrant. Most MS, as with consumption, congregate within the two left quadrants, representing reduced production of legumes, with many (including the EU-28 average) within the lower left (reduced animal production). This implies that production of both legumes and animal products have declined during the period 1993-2013, contrary to the period 1961-2013 (Figure 19).

These results evidence that across most of EU MS, consumption and production transitions are yet to be seen. This reinforces the need for identifying the present barriers and opportunities to such shifts, and for potential transitional pathways to shift these historical trends.

Present and Future EU Plant-Protein Situation

Current barriers and opportunities for protein-rich products

The basic results from the first workshop are presented in Table 11. From the two groups, 34 barriers and 23 opportunities for current EU plant-protein production and consumption were identified, with notable differences across the two groups.

Table 11. Elements identified in the two groups from Workshop 1

Group No.	Barriers	Opportunities	Total Elements
1	19	11	40
2	15	12	41

Barriers and Opportunities

In the first group (Figure 22a), the most voted barriers concentrated around agricultural factors (i.e. small farm size and farmers not used to protein-rich crops), in the second group (Figure 22c) barriers concentrated upon technological and product factors (i.e. production technology and organoleptic properties).

Figure 22. Barriers and opportunities within the EU plant-protein market.

Note: Brown line represents number of time factor was mentioned and green line the number of votes it received.

23 opportunities were defined by participants (Figure 22b and d), with far more in common across the two groups compared to barriers. Highly voted opportunities included dietary changes (movement towards greater consumption on protein-rich plant products), market development, and the environmental benefits of plant-proteins. That dietary changes were found to be one of the greatest opportunities in both groups, suggests its robustness. Further, it also outlines the stark contrast between the observed historical trends (Figure 19a) and the expected opportunities.

These results have demonstrated that at least from the perspective of Mediterranean stakeholders, a series of production and information barriers prevent greater contemporary production and consumption of plant proteins, like legumes. However, the perceived opportunity of future dietary changes and increased awareness of these crops would suggest a positive future. The identification of these opportunities emphasise the importance of analysing the near future and investigating what policy strategies could be implemented to take advantage of such opportunities.

Perspectives of the future of protein-rich products

145 elements were generated (Table 12) across the two backcasts (Figure 23 and Figure 24), with 82 generated in the first group and 63 in the second. In each group, these elements were more or less evenly distributed across element groupings (milestones, barriers, opportunities, and policy actions).

Table 12. Elements identified in the two backcasting exercises from Workshop 2.

Group	Milestones	Barriers	Opportunities	Policy Actions	Total Elements
1	19	19	19	25	82
2	18	17	14	14	63
Total	37	36	33	39	145

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Figure 23. Backcast from Group 1. Five identified strategies imposed.

Note: Black framed elements identified in Workshop 1.

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Figure 24. Backcast from Group 2. Four identified strategies imposed.

Note: Black framed elements identified in Workshop 1.

Milestones

In total, 37 were defined (19 in Group 1 and 18 in Group 2). Common milestone themes included:

- Increased funding for research and development of plant-proteins (2018)
- Availability of plant-protein products on the market (2019-21)
- Establishment of value and supply (production-processing-retail) chains for protein-rich products (2024-25)
- Development of new varieties of protein-rich crops (2026)

The timing of these milestones suggests the stakeholders' perceptions of the temporal feasibility for their achievement.

Barriers and Opportunities

Across the two groups, 36 barriers and 33 opportunities were identified. In both groups, barriers and opportunities identified from the first workshop were also included and unchanged in the second (elements edged in black in Figure 23 and Figure 24). In general, barriers were concentrated around the present or very near future (2018-2020) (Figure 23 and Figure 24). This may be explained by the fact that current barriers are often more evident than future ones, which may arise from unknown knock-on effects. Group 1 identified 19 barriers and Group 2 17. In the two groups three similar barrier themes were identified:

- High prices of protein-rich processed products may limit greater consumption (2018-2022)
- Low demand and a lack of knowledge of products also hinder consumption (2015-2020)
- Protein-rich product functional properties in terms of difficulty of protein extraction, lack of homogeneity in isolates, and the organoleptic properties and anti-nutritional factors of represent processing barriers (2016-2025)

From these results it is clear that stakeholders not only in Mediterranean countries, but across the EU perceive similar barriers for plant-protein products. With each of the most important barriers voted from the 1st Workshop (and presented to participants in the 2nd workshop) used in both backcasting exercises. These results would suggest the continuance of contemporary barriers into the near future and would need to be addressed.

In contrast to barriers, 33 opportunities (19 in Group 1 and 14 in Group 2) were spread out more evenly across the timelines. Although opportunities were distinct between the groups, repeated themes were evident:

- Health and environmental benefits (2020-2025)
- Dietary changes and increased consumer awareness (2021-2022)
- Marketability of products and improved access to information (2022)

As with barriers, participants in the second workshop perceived similar opportunities to those of identified within the first workshop. Once again, all opportunities from the first workshop

presented to participants in the second were used and placed upon the backcasting timeline. Current opportunities and opportunities for the future are tied around greater exposure and awareness of the products, their environmental and health benefits, and dietary changes.

Policy Actions

In total, 39 actions (25 in Group 1 and 14 in Group 2) were defined (Table 13).

Table 13. Policy actions needed to attain the desirable end-point from the backcasts. Most important policy actions identified by proportion of votes given to each. Only common policy actions across both groups are displayed.

Policy Actions	Group 1 Votes (%)	Group 2 Votes (%)
Development of local supply chains	15	2
Creation of plant-protein lobby	6	11
Development of agricultural practice guidelines	6	7
Increased consumer information	5	18
Increase in funding for research	4	14
Advertising and labelling of production and sustainability	3	2

In total, 6 common policy actions were identified by participants across the two backcasts. Despite these policy actions being common, their perceived importance was quite different. The development of local supply chains, increased consumer information, increasing in funding for research, and creation of a plant-protein lobby were voted as the most importance policy actions. Furthermore, it is interesting to note the suggestion of the creation of plant-protein lobby, which in both backcasts was set for the period 2020-21, implying the perceived urgency for its execution. The outlining of this action may suggest that stakeholders note the need for a counter-point to the perceived power of the meat and dairy lobbies, both identified as barriers.

Strategies

In total, 9 strategies (5 in Group 1 and 4 in Group 2) linking milestones with policy actions for achieving the desired end-point were developed in the two groups. Table 14 shows, common intermediate milestones, policy actions, and timelines for implementation are evident, as well as the themes of these strategies.

Table 14. Elements linked within defined strategies.

Group	Strategy	Milestones Attained	Policy Actions Required
1	1: Agricultural Research and Development	Breeding for improved cultivars (2022) Resistant cultivars (2023) Improved cultivars (yields) (2026) 10% Increase in protein-rich crop area (2028)	Investment in plant breeding (2018) Information and training for farmers (2019) Educational programs (2023) Support for agricultural training (2024)
	2: Development and Support of Supply and Value Chains	Value chain created (2024) Competitive protein crop markets (2028) 10% Increase in protein-rich crop area (2028)	Development of local supply chains (2019) Support for Local Protein Crops by the EU (2025) CAP supports (2027)
	3: Policy Supports	Change food industry profile (2019) Agricultural policy supports for legumes (2024) 10% Increase in protein-rich crop area (2028)	Creation of plant lobby (2021) Protective taxes on raw materials (2022) Increase import tax on soya (2026) CAP supports (2027)
	4: Consumer Education and Awareness	Development of new protein-rich dishes (2019) 10% reduction in animal protein consumption (2029)	Advertising and labelling of product production and sustainability (2018) Increased consumer information (2018) Consumer education activities (2021) Official EU animal welfare label (2022)

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		EU-scale marketing (2026)
	5: Processing Infrastructure Development	Improved plant production facilities (2019) New plant protein products on the market (2020) Expansion in processing plants for novel products (2023) Competitive protein crop markets (2028) Connection between established companies and start-ups (2018) CAP supports (2027)
2	1: Agricultural Research and Development	New varieties with higher yields and protein content available (2026) 10% Increase in protein-rich crop area (2028) Increased lobbying (2019) Increase in funding for research (2022)
	2: Development and Support of Supply and Value Chains	Sustainable extraction techniques developed (2022) Organic agriculture supported (2023) Fully established value chains for new protein products (2025) 10% Increase in Protein-Rich Crop Area (2028) Development of local supply chains (2020) Development of agricultural practice guidelines (2021) Certification of origin of production (2023)
	3: Policy Supports	20% increase in price of animal product (2025) 10% reduction in animal protein consumption (2028) Increased lobbying (2019) Increase in public supports (2021)
	4: Consumer Education and Awareness	New plant protein products on the market (2020) Increase in consumer awareness of products (2021) 30% of consumers eat plant proteins regularly (2023) Increase in consumer awareness (2025) Increased consumer acceptance and consumption of plant proteins (2026) 10% reduction in animal protein consumption (2028) Increased consumer information (2018) Dissemination of educational material of benefits (2020)

Robust Strategies

In evaluating these 9 strategies, and following the plenary discussion with participants, 4 robust strategies or sustainable transitional pathways towards the goal of increasing plant-protein production by 25% and increasing consumption by 10% were developed:

Robust Strategy 1: Agricultural Research and Development

Increased investment in research (~2018-22) for crop breeding (~2022) is implemented to improve protein-rich plant varieties for improved disease resistance (~2023) and higher yields (~2027), making these crops more attractive to farmers. Improved crop varieties result in increases in area dedicated to protein-rich crops across the EU (~2028). Expansion of new cultivars is dependent upon information and support for agricultural training (~2024). Means for achieving these increases in funding would be through the development of a protein-crop lobby (~2019).

Robust Strategy 2: Development and Support of Supply and Value Chains

Formation of local supply chains (~2019) encourage creation of value chains for protein-rich crops (2024-26) and expansion in protein-rich crop area (~2028). The establishment and consolidation of these chains are supported and encouraged by supports for local protein-crop and organic production (2023-24), as well as through supports from the most recent reform of Common Agricultural Policy (CAP) (~2027).

Robust Strategy 3: Consumer Education and Awareness

Advertising is expanded to increase exposure of protein-rich crop products (~2019), with labelling improved (~2019) to increase consumer information (~2019-21). Improved consumer education (~2021) is supported by dissemination of educational media to improve

understanding of consumption and production benefits. Increased exposure to products and information drives greater consumption (~2023) and acceptance (~2025) of novel plant-based products.

Robust Strategy 4: Policy Supports

The formation of a protein-crop lobby (~2019) encourages greater national public (agricultural) policy supports (~2022-24) directed towards protein-rich crops, leading to increased supports from the CAP (~2027). This results in a competitive protein crop market (~2028) and increases in areas dedicated to protein crops (~2029). Further support mechanisms are used to increase taxes on imported soya (~2026) and establish protective taxes to encourage greater use of EU-produced raw materials (~2023). Policies are also implemented to increase prices of animal protein products (~2025).

3.4 Protein-rich legume and pseudo-cereal crop suitability under future European climates

The potential for nascent consumption transitions in Europe, supported by European grown protein-rich plant-based animal product replacements, are likely to depend upon abiotic suitability and crop distributions. However, to gauge how future production agricultural systems may increasingly incorporate protein-rich crops, it is important to understand how current and future climates affect crop distributions across the European Union.

Current Protein-Rich Crop Distribution

The results from the analysis of current protein-rich crop distribution are presented in Figure 25. For illustrative purposes, each relationship is displayed with a non-statistical theoretical expected relationship between distribution and suitability (dashed line). Suitability is expected as a limiting factor, so more points should be under this line than above it. Quantile regression lines (red line), derived from regressions of the 95th quantile of crop distribution values and suitability for each crop are also included. Regression lines are only plotted if a relationship was found to be significant ($p < 0.05$).

For all crops the majority of the points is below the dashed line, confirming the hypothesised asymmetric relationship between suitability and production. In most cases, crop distribution is far below what may be expected from its suitability. Buckwheat (Figure 25g and Figure 25h) is a particularly good example of this. Production only occurs in regions with near perfect conditions, with the distribution of this crop being far below what may be expected. This suggests that other factors, beyond climatic suitability, are important when it comes to protein-rich crop choice.

Figure 25 also displays that at the 95th quantile of crop distributions, climatic suitability is significantly related to distribution for soya and faba bean (max and mean suitability), and blue lupin under max suitability. Other relationships were found to be marginally insignificant at the 95th quantile of suitability results, but in most cases this is because crop production occurs only under optimal conditions, limiting the range of suitability values for the regression analysis.

These results reveal not only that climatic suitability is a limiting factor for protein-rich crop distributions across the EU, but also that in many cases these crops are widely under cultivated, considering their suitability. This result would infer the latent and under-utilised potential of many of these crops. Soya (Figure 25a and Figure 25b) offers an interesting result with many regions over cultivating relative to climate suitability and under cultivating despite high suitability in other areas. Those regions in lower-right of Figure 25a and Figure 25b are in Greece, Italy and Spain, suggesting that other protein-rich crops are being cultivated in these area, despite near perfect conditions for irrigated soya production.

Figure 25. Relationship between crop distribution and maximum and mean crop suitability at EU-28 NUTS-2 level.

Note: Quantile regression lines (red line), derived from the 95th quantile are plotted if crop distribution and climatic suitability relationship was significant ($p < 0.05$). Dashed line represents non-statistically supported theoretical expected relationship between distribution and suitability.

The same analysis as displayed in Figure 25 was also performed using crop yield data, instead of crop distribution data. The outputs of this analysis (Figure 26) present no significant relationships between climate suitability and yields, at the 95th quantile. This result indicates that a range of other factors are responsible for yields, or may also suggest limited quality of yield values from agricultural census, with recorded yields being higher or lower to actual yields.

Figure 26. Relationship between crop yields and maximum and mean crop suitability at EU-28 NUTS-2 level.

Future Protein-Rich Crop Suitability

Outputs from the model demonstrated that climate change could have widespread impacts upon the suitability of protein-rich crops across EU-28 MS (See Annex 8: tabulated results of average percentage suitability changes for all crops across EU-28 countries). Traditionally important producers of protein rich legumes including Spain, France, and Italy were modelled to be particularly vulnerable to future climates. These countries saw respective average suitability changes to common bean (-5.7%, -15.2%, and -2.8%), faba bean (-4.9%, -8.4%, and -0.8%), chickpea (-5.5%, -12%, and -0.9%), and lentil (-4.8%, -7.3%, and -0.9%). In contrast, northern European countries saw suitability increase for these crops: Denmark (19.7%, 12.2%, 22.3%, and 15.9%), the Netherlands (3.2%, 6.1%, 9%, and 7.1%) and the UK (20.9%, 6.4%, 6.7%, and 7.3%). These geographically divergent patterns were also replicated for novel crop species like amaranth, quinoa, and Andean lupin.

Crop suitability results for all analysed crops are presented in Figure 27, with variation in suitability outputs under the different conditions of all GCMs displayed. The results support the heterogeneous nature of impacts across both countries and crops, with suitability largely increasing in northern and central Europe and reducing across the south. Chickpea (Figure 27b) and common bean (Figure 27h) exhibit the greatest variations in suitability change, with such variation appearing not to be geographically linked. Blue lupin (Figure 27e) and soybean (Figure 27f) both show greater suitability changes than the previous four crops (Figure 27a-d). In some cases suitability was modelled to increase by up to 800%, compared with a maximum of 300% for the previous four. Furthermore, Figure 27f highlights the relatively limited suitability of soya at national scales in Europe, with only 23 countries showing suitability under the baseline. The majority of these countries had suitability values of less than 0.1. In those countries where soya was suitable, climate change largely improved suitability. Furthermore, Figure 27 infers the limited impacts of modelled soil pH in affecting crop suitability, with only the suitability of quinoa (Figure 27d) and blue lupin (Figure 27e) found to be limited by this parameter in 2050, demonstrated by the green fill of the boxes. For these crops soil pH suitability was identified as being the limiting factor in Nordic countries.

Figure 27. Percentage changes in suitability from baseline (1970-2000) under future (2050) climates.

Note: Boxes represent results for each crop and country, for all 30 GCMs under the RCP4.5 climate scenario. Values in brackets demonstrate national suitability under the baseline conditions. Box colours represent the limiting factor of suitability for each crop, with grey representing climatic conditions and green soil conditions

Spatial patterns of future suitability across the EU are displayed in Figure 28. These results present average suitability values from the outputs of all the models run for the 30 GCMs. In 2050, areas identified with high suitability for protein-rich crops were concentrated within Adriatic countries, alpine regions (northern Italy, Slovenia, southern Germany, and Eastern France), and northwestern Europe. These high levels of suitability may also be able to account for recent increases in production across some Adriatic countries (Figure 21). However, in some of these regions suitability for a number of crops was modelled to decline (i.e. faba bean and chickpea in Croatia). Further, quinoa and to a lesser extent blue lupin were found to have high suitability across a range of environments. High quinoa suitability (Figure 28d) was observed from the Atlantic coast of Portugal, to the Eurasian Steppe. In contrast, regions highly suitable for soya (Figure 28f) are almost exclusively concentrated in the Adriatic, with lesser suitability seen in southern Germany and Ireland.

Figure 28. Geographical representation of average future suitability (2050) generated from 30 GCMs under RCP4.5.

Note: 0 (red) represents unsuitable conditions, and 1 (purple) suitable conditions. White pixels represent lands not cultivated under the baseline

Climate Proof Protein-Rich Crops

Under the baseline conditions (Figure 29a), quinoa was found to be the most suitable crop across almost 70% of European arable land followed by: blue lupin (23%), common bean (4%), and white lupin (1.4%). However, by 2050 (Figure 29b) and suggesting the impacts of climate change, a more diverse cropping structure is observed. Despite this, quinoa still dominates, representing the most suitable crop in more than 36% of European arable land followed by white lupin (19%), blue lupin (19%), and common bean (15%). Further, 21 multi-crop options covering ~10% of European arable land were identified. The presence of these multi-crop options correlates with the regions of high suitability identified in Figure 28.

Figure 29. Robust protein-rich crop options under baseline and future climates conditions.

Sensitivity Analysis

Table 15 displays how changes in the parameters for each test affect how suitability responds under present and future conditions. Suitability is characterised into three categories: increase, neutral, and decrease. These categories represent changes from present climatic conditions to future conditions. The below tabulates how changes to parameters can alter these categories, with five categories developed to highlight how parameter changes alter suitability, compared to the baseline. The results display the number of crop country combinations (e.g. quinoa suitability in Sweden) affected by the parameter changes, based upon average national suitability values for each crop.

The results demonstrate that under all sensitivity tests (Table 7), the greatest number of category changes (increase, decrease, and no change) in crop-country combinations were seen for the ph-25%+1m test, compared to the baseline results. Under the conditions of this sensitivity test, 32% of crop-country combinations changed, with 31% changing for the Tmin+2C+1m and the Pre+25%-1m tests. Complete changes in suitability outputs (increase to decrease, or decrease to increase) ranged from 1-19% across the sensitivity tests. The greatest changes being a positive shift from decrease to increase. The sensitivity results, although suggesting higher sensitivity to previous analysis (Manners and van Etten, 2018), still demonstrate the moderate level of sensitivity of EcoCrop outputs to parameter changes and the robustness of the model.

Table 15. Sensitivity analysis results.

Scenario	No Change		Increase to Decrease		Decrease to Increase		Neutral to Increase or Decrease		Increase or Decrease to Neutral	
	Crop Country combinations	%	Crop Country combinations	%	Crop Country combinations	%	Crop Country combinations	%	Crop Country combinations	%
Tmin+2C+1m	242	69	7	2	65	19	21	6	16	5
Tmin-2C+1m	277	79	17	5	29	8	19	5	9	3
Tmax+2C+1m	275	78	8	2	36	10	20	6	12	3
Tmax-2C+1m	276	79	15	4	29	8	20	6	11	3
Pre+25%+1m	266	76	4	1	38	11	14	4	29	8
Pre-25%+1m	246	70	23	7	50	14	26	7	6	2
pH+25%+1m	266	76	17	5	29	8	21	6	18	5
pH-25%+1m	237	68	7	2	61	17	22	6	24	7
Tmin+2C-1m	271	77	8	2	31	9	14	4	27	8
Tmin-2C-1m	270	77	34	10	12	3	13	4	22	6
Tmax+2C-1m	300	85	12	3	8	2	12	3	19	5
Tmax-2C-1m	291	83	19	5	6	2	13	4	22	6
Pre+25%-1m	242	69	13	4	24	7	15	4	57	16
Pre-25%-1m	263	75	31	9	17	5	28	8	12	3
pH+25%-1m	272	77	32	9	8	2	12	3	27	8
pH-25%-1m	257	73	18	5	31	9	14	4	31	9

Note: Total suitability changes for each crop in each country across the sensitivity results. Value in brackets represent percentages.

4. DISCUSSION

Forest losses represent a challenge for humanity in terms of climate change, biodiversity loss, and ecosystem service functionality (Nepstad et al., 2008; Peres et al., 2010; Oliveira et al., 2013; Lapola et al., 2014; Keenan et al., 2015; Machovina et al., 2015; Baccini et al., 2017). The complexity of this land-use change and its intertwined and globalised drivers are suggestive of the utility of the application of a holistic, multi-scalar, and interdisciplinary methodological approach to address it.

The efficacy of such an approach is evidenced by the development and implementation of a metric for quantifying how socio-economic factors can contribute to forest vulnerability and mapping how temporal and spatial fluxes in these factors can result in considerable vulnerability changes. The Deforestation Vulnerability Index (DVI) provides a multi-scale insight into the dynamic role that socio-economic factors have had in driving vulnerability across LAC forests in recent years. In general, vulnerability was found to have reduced across much of the continent. These declines were attributable to reductions in agricultural area growth and governance improvements. The positive effects of governance and institutional improvements are, following the literature, to be expected. McNeil et al. (2012) outline the constraining effect that poor governance can have on sustainable development. The specific and beneficial role of governance and institutional improvements in forest conservation and communities is increasingly being established (Rodrigues-Filho et al., 2015; Caviglia-Harris et al., 2016). Governance improvements coupled with social and supply chain initiatives have been repeatedly cited as potential avenues for reducing deforestation and limiting agricultural area growth in Latin America (Nepstad et al., 2014; Rodrigues-Filho et al., 2015; Gibbs et al., 2015). Müller et al. (2014) and Høiby and Zenteno-Hopp (2015) suggest that little progress can be made to conserve forests if good policies are subject to poor governance, or if policy conflicts exist.

The results from the DVI advocate the benefits of policies dedicated towards governance and institutional improvements. Such improvements could provide a route to ensuring natural resource conservation and subsequently reduce deforestation. However, despite contemporary improvements in governance across many Amazonian countries in recent decades (World Bank, 2016), implementation of governance reforms may be challenging, especially under increasingly turbulent political landscapes, exemplified by the current political situation in Brazil (e.g. Bragagnolo et al., 2017). Further, potentially intangible (in the short-term) and time consuming governance and institutional reforms may be unpalatable for voter conscious and electioneering administrations. Governments wanting to appear proactive in terms of rural development and environmental conservation may consider other, more palpable options (Cuiza, 2017). The benefits of institutional reforms may only be reaped in the long-term, by which time governments may have changed and the benefits of change lost for the implementing administration. This may highlight the space for market-based interventions (e.g. Nepstad et al., 2014; Gibbs et al., 2015).

The DVI provides an illustration of how ephemeral and temporary vulnerability reductions stemming from governance improvements may be, with the identification of a vulnerability peak

in 2005. On closer inspection of the data, this peak can be linked to a continent-wide reduction in governmental efficacy, political stability, and regulatory quality (World Bank, 2016). Analysis of historical election data offers an explanation for such declines. The period 2004-2006 saw continent-wide legislative and/or presidential elections (University of Texas, 2010). Examination of the literature highlights precedence for these findings and their implications for forest conservation. Electoral periods have been 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). These observations are suggestive that although improvements in governance may reduce vulnerability, these reductions may only be based upon perception and are easily lost. Conservation of natural resources therefore may be dependent upon the perception of consequences for illegal actions. As such institutional improvements, which may only be perceived for example through greater physical displays of policy (i.e. more forest managers or wardens), may assist in providing greater protections to forests.

Smith et al. (2014), and FAO (2015b) both observe that reducing/stabilising deforestation rates have been identified across LAC countries. 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. Identified declines in vulnerability from the DVI are somewhat inconsistent to the observed, albeit reducing rates of deforestation (FAO, 2015b). A number of factors may have contributed to such differences. The omission of indicators of vulnerability due to: a lack extensive data (e.g. land tenure), them falling outside of the scope of the analysis (e.g. physical characteristics like slope and aspect), or them not being identified (Vincent, 2004) may be accountable. Additionally, these differences may also expose the existence of a lag between socio-economic improvements and 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, as per the Forest Transition model (Mather, 1992). The presence of such a lag may be supported by the FAO (2015b) (See Annex 1: Latin American and Caribbean forest area and forest area changes from 1990-2014), where deforestation rates for the period 2010-2014 were found to have further declined in countries where vulnerability reduced from 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.

Results from state-scale application of the DVI support the concept of complexity and variability at sub-national levels (Simane et al., 2016). Application of the index at the state-scale revealed not only its flexibility, but also the disparate vulnerability at distinct scales. The Department of Santa Cruz (Bolivia) and the State of Pará (Brazil) are both on the respective front-lines of their national agricultural frontiers. Both regions have high levels of agricultural area growth and economic dependence upon agriculture. Santa Cruz does however have lower governance quality than those seen within Pará. Their high economic dependence upon agricultural activities and rapid expansion in agricultural area (INE, 2011; FAPESPA, 2017) explain their elevated vulnerability. These results reinforce 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 within a single country. These differences stress the need for specific and, where possible, localised management strategies to address vulnerability heterogeneity and respond to deforestation threats. They also suggest that localised focus upon improving governance and implementation of policies could be a pathway to reducing forest vulnerability at more local scales. The results further demonstrate the utility of the DVI, it 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 detailed perspective of forest vulnerability. 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.

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's 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 (e.g. Mildrexler et al., 2016; Amalina 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.

The identified differential in national and state vulnerability demonstrates the importance of evaluating processes like deforestation at the smallest scale possible to gain a more resolved and informed idea of the processes and decision-making behind it. Elevated vulnerability at state-scale in agriculture-forest interfaces may have been supported, indirectly, by policies and decision-making encouraging rural development through agricultural expansion and natural resource extraction (Diversi, 2014). In some instances, such policy-making has successfully catalysed socio-economic improvements (Le Tourneau et al., 2013). However, Ioris (2016) established that concentrating solely upon agricultural intensification and/or resource extraction may provide only marginal socio-economic gains, and may be responsible for long-term environmental costs (Weinhold et al., 2015). Conversely, conservation policies have been implicated as drivers of outward migration and reduced settlement (Carr, 2009), confining local communities to conditions of poverty (Chomitz, 2007), and hindering sustainable development (Guedes et al., 2014).

This investigation reinforces the well documented trade-offs between regulating and provisioning ecosystem services in agricultural systems (Raudsepp-Hearn et al., 2010; Carreño et al., 2012; Phalan et al., 2011; Lee and Lautenbach, 2016). The results outline that focussing simply on farm-scale income (and the potential associated socio-economic benefits) can have negative impacts upon natural resource conservation (farm-scale net sequestration of carbon)

and vice-versa. The impacts of the binary choice between these antagonistic goals can be stark, with decision-makers having to make substantial compromises. The results offer an insight into the sensitivity of these ES relationships to decision-making, bolstering suggestions of Bennett et al. (2009). Extreme management preferences were found to aggravate ES trade-offs markedly. Managing trade-offs, whilst supporting ES provision is essential for sustainability (Cavender-Bares et al., 2015). In this regard, the goal programming modelling establishes a series of repeated intermittent solutions that may offer sustainable management options for all farms types. Fooks and Messer (2012) suggest the repetition of these solutions demonstrate their robustness, and they may represent viable management options (Schroder et al., 2016). These solutions could provide points of reference in the development of strategies sensitive to the nuanced effects of decision-making in such dynamic and important regions. Identification of these management option reinforce the utility of modelling ES relationships (Viglizzo et al., 2006; White et al., 2012). Application of balanced management strategies resulted in relatively stable farm sequestration and incomes. More extreme preferences drove large variations in income and especially sequestration, with these most extreme results seen in favour of income maximisation, where forests were widely deforested, with subsequent impacts upon carbon sequestration, reflecting the current reality of the region (Davidson et al., 2012; Varela-Ortega et al., 2014).

As a means of addressing these antagonistic relationships and following suggestions within the literature (e.g. Sayer et al., 2013), the identified ES trade-off relationship were analysed under the conditions of hypothetical policy scenarios. Under moderate management preferences, implementation of a conservation oriented scenario encouraged future farm-scale income and carbon sequestration gains compared to a baseline, with implementation of an agricultural development policy scenario encouraging similar gains in income, with limited costs to sequestration. The results propose the potential success of a policy scenario based upon conservation of ecosystem services, in improving farm income, protecting carbon sequestration, and conserving forest area. The long-term importance of the introduction of such a policy is suggested by Tejada et al. (2016), who found that limiting future environmental degradation, specifically deforestation, without offering new economic alternatives is unlikely. These are important observations considering the benefits of forest protection for ES (Brandon, 2014) and that well managed forests may provide a more robust income stream than agriculture under climate change, with forest protection offering a climate change adaption mechanism for rural communities (Wunder et al., 2018).

Moving from the modelled world to the real, where implementation of such policies requires consideration of social acceptability, likelihood of implementation, willingness of politicians and institutions to reform, and funding availability may result in complications. The applied policy scenarios would be heavily dependent upon a system where environmental monitoring is available, and an effective governance system to implement policies is in place. The importance of strong governance apparatus having already being established by the DVI. However, Varela-Ortega et al. (2014) suggest that such systems are absent in the region and are likely to act as a barrier to a sustainable future (Varela-Ortega et al., 2015). Furthermore, these policy scenarios (especially Conservation of Ecosystem Services) represent a considerable financial cost,

suggesting the necessity of long-term funding to sustain them. However, such funding is invariably scarce (James et al., 1999; Ferraro and Pattanayak, 2006). Despite recent suggestions of the availability of unlocked funding resources (World Bank, 2015), there are still disconnects between funding potential and actual funding (Clark et al., 2018). Domestic policy-makers will need to be encouraged to release sufficient funds (Sethi et al., 2017), or barriers to private financing (Clark et al., 2018) will need to be addressed to resolve these financial obstacles. Further, implementation of these policies may be challenging, especially under increasingly turbulent political landscapes. Intangible (in the short-term), financially costly, and time consuming policies, as mentioned earlier, may be once again unpalatable for voter conscious administrations.

This analysis enlightens the complex and antagonistic environment within which contemporary policy makers and decision-makers find themselves in agriculture-forest systems. Increasingly under pressure to balance competing goals, under such precarious circumstances a balance is often not achieved (Börner et al., 2007; McNeil et al., 2012; Ioris, 2016; Nobre et al., 2016) and may be unlikely under the current political landscape (Tejada et al., 2016). In consideration of these circumstances, in situ application of models such as the multi-objective goal programming model may assist in developing more realistic and viable alternative management solutions, to avoid such conflict-ridden states. Such application may aid in identifying and developing common attractive solutions amongst stakeholders and simultaneously formulate a dialogue amongst stakeholders to find a balance between antagonistic objectives. Dialogue establishment could also encourage mutually beneficially social learning and trust building amongst stakeholders (Cáceres et al., 2015). Finally, such dialogue could aid in developing context specific and tailored policy responses, which according to Pinho et al. (2014) are necessary to encourage conservation and limit poverty in tropical forest systems.

Although quantifying the exact role of consumption and production changes in driving these trade-offs may be impossible, global dietary transitions are entrenching environmental degradation (Godfray et al., 2010; Foley et al., 2011). Greater consumption of animal products has already been shown to be responsible for increased production of livestock and feed commodity crops in LAC countries, with subsequent effects on forest area (Aide et al., 2013). In particular, the production of soya for oil and meal, as a replacement source of protein for global animal feeds, has become one of the driving forces in global soybean production (Dei, 2011). During field-work in the Province of Guarayos (Bolivia), recently deforested lands (on non-subsistence farms) were found in many cases to have been, or in the process of being, converted to soya production. In the Department of Santa Cruz, soya cultivated area has almost tripled since the turn of the millennium (with similar patterns seen in Pará, Brazil). Statistics from the FAO and UN Comtrade highlight that in terms of weight (2.8 MT), more than 20% of Bolivian soya production in 2013 was exported as raw beans, with a further 50% as soya-cake (UN Comtrade, 2017; FAO, 2018b). These figures demonstrate the importance of external markets (de Visser et al., 2014; Zander et al., 2017) and indirectly dietary changes for Bolivian soya production and consequentially forest area and ES functionality. These patterns are repeated across much of Latin America, especially in Paraguay, Uruguay, Argentina, and principally Brazil (UN Comtrade, 2017; FAO, 2018b).

These dietary changes, not only represent a societal challenge (Tilman and Clark, 2014), but also an environmental hazard (UNEP, 2010). Despite the environmental and health warnings, global consumption of animal products was found to have increased by 32% since 1961, following trends identified by Sans and Combris (2015). Increments in consumption of animal products were especially acute in Asia, where meat consumption increased 6-fold. These findings reinforce Vranken et al. (2014) who state that as incomes increase, parallel increases in consumption of meat are observed. In contrast, long-term global consumption of potential meat replacement options, like legumes, were found to have reduced by 21%. Recent global increases in per capita consumption of legumes are encouraging, even under the proviso that such increases are relatively small. Analysis of global production patterns highlight that animal product production has trebled. These increases are most acute in economically growing continents and are stabilising in wealthier regions, reflecting Rae and Nayga (2010). Identified shifts within the composition of global meat consumption from beef to poultry may, according to Saxe et al. (2013), substantially reduce the environmental impacts of meat consumption. However, both Audsley et al. (2010) and de Vries and de Boer (2010) dispute this, suggesting that such shifts could increase demand for land-use. In contrast, production of legume crops has increased, but at far gentler rates, compared with animal product production. These results illustrate that globally, consumption patterns appear not to be changing tack, but continue towards greater consumption of animal products.

Transitions from animal product consumption to legumes or plant-based products are not currently expected globally, but are more likely in wealthier regions (Vranken et al., 2014). Across the European Union, aggregated consumption of meat and dairy products were observed to have stabilised, supporting both de Boer et al. (2006) and Vranken et al. (2014). Despite the stabilisation, little evidence of consumption transitions towards protein-rich legumes and away from animal products was identified. In fact, a number of larger, wealthier MS (e.g. Germany and the UK) increased their per capita consumption of animal products, contrary to expectations (Vranken et al., 2014). These patterns were also evident in traditional producers and consumers (Mediterranean MS) of legumes who were all identified to be reducing legume consumption, but with distinct patterns of production. These results demonstrate the clear need for country specific policy interventions to address these heterogeneous patterns and governmental leadership to shift diets away from unhealthy patterns, a point outlined by Wellesley et al. (2015). Only a handful of EU-28 countries saw consumption of legume crops increase, whilst simultaneously seeing animal product consumption reduce (e.g. Austria, Czechia, and Hungary). That so few countries were found to see positive changes would suggest that EU-scale consumptions transitions remain distant.

Across the EU, dietary land use is now dominated by animal protein production, with demand from other potential protein sources reducing (Kastner et al., 2012). These findings are reflected in the results of this investigation, where production of animal products is orders of magnitude greater than that of legumes in the EU. Production of potential meat replacements like protein-rich legumes was found to be declining across the EU-28, with few EU MS seeing production transitions. This observation is concerning considering the negative consequences of continued

animal protein production (Tilman and Clark, 2014; Schader et al., 2015; Erb et al., 2016). In contrast, production of legumes was observed to fluctuate extensively, with long-term declines in total production and area dedicated to these crops across the EU. Analysis of the impacts of the CAP on legume production across the EU is suggestive of specific, rather than general successes. Unfortunately, these successes were found to be limited and focussed upon certain leguminous crops (peas). These findings echo Watson et al. (2017) and Zander et al. (2017), where EU agricultural policies were considered to have had limited effects in encouraging production of leguminous crops sufficiently to reverse long-term declines.

However, decision-making behind crop cultivation is far more complex than consideration of agricultural policy and subsidy provision. As noted by stakeholders, a series of barriers may help to explain why, despite agricultural policy supports, legume production was found to be so volatile and will need to be addressed by future agricultural policies. Lack of crop knowledge, lack of production technology, product properties, and farm sizes were identified to inhibit EU production, with the literature also suggesting farm intensification, abandonment of traditional agricultural systems, and low prices as important factors in legume production (Voison et al. 2014; Cernay et al., 2015).

The direct outcomes of such barriers may be tangible in the observations made by Magrini et al. (2016) and supported by this investigation that cultivation of many legumes in EU-28 MS is done in unsuitable conditions. These observations may also account for the low and unstable yields identified by both stakeholders and the European Parliament (2013) as barriers to production. These findings may be the result of the systemic lock-in, where European agriculture has increasingly favoured cereals over recent decades, to the detriment of other crops (Voisin et al., 2014; Magrini et al., 2016). The perceived instability of yields may have tainted the image of legumes to modern European farmers and infers the circular nature of this problem. To address these issues, the barriers and potential policy lock-ins will need to be recognised and confronted to free legume production from their current constraints.

Despite these barriers, stakeholders' suggest various opportunities for encouraging both production and consumption of these products. The perceived inevitability of dietary changes towards greater consumption of plant protein-rich products is particularly interesting. Stakeholders even suggest a self-supporting policy mechanism for encouraging these changes, through increased awareness campaigns. Keats and Wiggins (2014) already highlight how such campaigns have been a successful policy mechanism for achieving consumption shifts.

According to the results of the backcasting exercise, to encourage greater production of legumes in the EU, investments in agricultural research should become a focus of future EU policies. Research investments could have a liberating effect upon legume production across the EU. Such a policy is not without precedence within the EU, where focussed research investments were successful in stimulating pea production (Magrini et al., 2016). The benefits of such a policy could also address the aforementioned agronomic barriers affecting legumes (e.g. Watson et al., 2017). Greater research investments in breeding programmes could result in development of more resistant and higher yielding crop varieties. These investments have also been called for as a

mechanism for ensuring nutrient security from leguminous crops under climate change (Manners and van Etten, 2018), which is predicted to have a large impact in certain regions of Europe, as highlighted within this document.

Stakeholder also suggest that EU policy focus should shift towards the completion and support of supply and value chains for protein-rich crops, like legumes. Magrini et al. (2016) outline the inhibitory effects of incomplete supply chains for legumes, a point reflected in both phases of the participatory assessment. Ranganathan et al. (2016) evidence the benefits of complete and well-resourced value chains, highlighting how investments in livestock value chains contributed to consumption increases. Stakeholders insist the crucial role of multi-scale governments (regional-supra national) for this policy strategy. Voisin et al. (2014) demonstrate previous governmental successes of supply chain supports, through creation of niche markets and labelling.

A decade after Schneider (2002) posited that a lack of information concerning the benefits of legumes and a lack of product adaptation to modern consumption patterns may have limited their production and consumption, De Bakker and Dagevos (2012) reinforced the need for consumer education concerning the environmental impacts of animal-based products, coupled with the health and nutritional benefits of plant-based products. Awareness of animal products' environmental impacts has been repeatedly found to be low among western consumers (Lentz et al., 2018). According to stakeholders, this lack of information continues to affect EU consumers. Ritchie et al. (2018) state that without movement in consumer attitudes concerning animal-based products, consumption shifts are unlikely. Stakeholders noted and addressed these concerns, stating that to reduce animal product consumption, increase animal replacement products' acceptance, and shift towards greater legume consumption would require EU-scale improvements in consumer education and information availability. Although stakeholders consider that improved consumer awareness of the benefits of plant-protein and legume consumption as an opportunity, the EU and individual MS should consider educational policies as a conduit for encouraging consumption changes and take advantage of this perceived opportunity. Governments have historically had policy successes in encouraging and promoting consumption shifts through educational activities (Keats and Wiggins, 2014). Wellesley et al. (2015) establish that the general public expect governmental leadership to reduce the consumption of unhealthy products. Stakeholders suggest that marketing campaigns, which follow information and education campaigns, coupled with improved labelling and exposure to novel products, could assist in shifting consumer perceptions and increase awareness of the environmental and health impacts of animal products.

Increases in public supports and implementation of taxes is the final strategy suggested. To increase production, stakeholders noted that national or supra-national agricultural policy supports were required. Such a policy is not without precedence within the EU, where focussed research investments were highly successful in stimulating pea production (Magrini et al., 2016). Stakeholders reinforce the continued need of these supports for encouraging EU production of legumes. Stakeholders also stressed the need for taxation upon non-EU produced protein-rich crops, like soya, supporting calls from Zander et al. (2017). Stakeholders also stated the need for

protective taxes to encourage use of local raw protein-rich materials in plant-based products. However, such protectionist taxation could have international trade implications, considering the EU's global trade agreements. Stakeholders summarised that application of taxes on animal-based products could also be used to reduce consumption. This echoes calls from the literature for such measures (Springmann et al., 2017; Poore and Nemecek, 2018). Nordgren (2011) argues the wide-ranging benefits of taxing meat consumption, with Springmann et al. (2017) noting the benefits of carbon intensity related taxation, coupled with subsidies for food groups with positive health and environmental impacts. Saxe et al. (2013) however caution the likely political, industrial, and social opposition to such a strategy.

The above strategy, along with that for increased research funding would, according to stakeholders, hinge upon the development of a plant-protein lobby. This action was recurrent across the backcasts, indicating its robustness and necessity. The development of such a lobby could provide an immediate counter-point to the perceived power of the meat and dairy lobbies.

Although these strategies have been defined individually, it is evident that their application in the real-world could not be mutually exclusive, being in many cases interdependent. For example, lobbying for greater supports for legumes and increased investment in research may be far more successful with greater citizen awareness and interest in their benefits. Improved consumer education would also encourage the completion of the supply chains, as farmers and companies would recognise the benefits of following consumer demands. Proposed policy suggestions could be considered individually or as part of a supra-pathway, taking advantage of their interconnectedness (as perceived and demonstrated by stakeholders in the backcasts), to encourage a series of virtuous circles towards more desirable futures.

The implementation of this combined approach has allowed for an improved understanding of historical trends, current barriers and opportunities, and potential pathways to the future for consumption and production of animal products and legumes at multiple scales. The inclusion of stakeholder knowledge within this original approach allowed for the incorporation of distinct interpretations of this of such a complex problem. de Bakker and Dagevos (2010) stress the importance of such knowledge when analysing societal scale problems such as consumption changes. Furthermore, inclusion of diverse and stakeholder based knowledge backgrounds may have aided in the development of strategies that may be more societally suitable and acceptable (van de Kerkhof, 2006). The application of the backcasting approach was highly beneficial in the development of these strategies, as it helped to remove the restrictions normally associated with analyses of the future (van Vliet, 2011). It also allowed stakeholders to envision how contemporary production and consumption patterns can be altered in a step-wise fashion to achieve a more desirable future outcome through strategy development.

The potential of these, or any strategies for encouraging protein-rich crop production, to reduce EU protein deficits and increase consumption of animal product replacement products would have to be considerate of other major future global changes like climate change. Curiously, as part of the backcasting assessment stakeholders neither defined climate change as a barrier nor an opportunity when developing strategies. However, understanding how current crop

distributions are correlated with climate and how climatic changes might affect future distributions are important sources of uncertainty for any potential production strategy. Addressing this uncertainty may assist in developing more climate resistant planning strategies that can support dietary and production transitions.

The results from the current crop distributions demonstrate that climatic suitability presents a limiting factor for contemporary distributions of protein-rich crops across the EU. The results also establish that in many regions of the EU protein-rich crops are not included in crop portfolios, despite high suitability. This infers the impacts of competition in productive environments for protein-rich crops. In the case of EU production of soybean, high suitability across much of southern Europe was not found to be associated with large areas of production. In many cases, common pea was found to be produced in these regions, despite identical suitability. These points may suggest the influence of other, non-climatic, drivers in crop choice in these regions. The benefits of identifying this protein-rich crop competition and the diversity of cropping options may be increasingly important as climates increasingly change. Informed farmers could use this information to shift cropping choices to protein-rich crops better adapted to new climatic conditions (Seo and Mendelsohn, 2008).

Encouragingly, climate change was found to represent an opportunity for many protein-rich crops. This potential is especially acute outside of current distribution patterns, supporting Stoddard et al. (2009). The outputs of this modelling mirror Iglesias et al. (2012) and Zabel et al. (2014) and the divergent effects of climate change on European agriculture. Northern Europe saw suitability increases, and in southern Europe culturally important species saw suitability reduce, consistent with previous studies (FAO, 2012; Valverde et al., 2015; Ramirez-Cabral et al., 2016). Salon et al. (2011) found that cool-season legume species (faba bean, lentil, lupins, pea, and chickpea) are particularly sensitive to abiotic stresses, compared to warm season (pigeon-pea, cowpea, and soybean). These findings are evident in the modelling, with faba-bean, lentil, lupins, and pea suitability declining in southern regions and increasing in northern parts of Europe. In particular, common bean and chickpea were found to see the greatest suitability declines in southerly regions. These results are suggestive of the need for increased research and breeding activities to address the stress related sensitivity of these crops (Zurita-Silva et al., 2014; Araújo et al., 2015; Santra and Schoenlechner, 2017). The outputs of this modelling stress the urgency of these activities especially across southern Europe. However, this call comes within the context of findings from Kwak and Gepts (2009) and Berger et al. (2012) who highlight that some cultivated protein-rich species exhibit limited genetic diversity and require breeding with wild relatives to improve tolerances.

Stoddard et al. (2009) and Daryanto et al. (2017) both suggest that limited breeding activities, coupled with a lack of investment have driven higher abiotic stress sensitivity and subsequent yield problems for legumes, compared to cereals. Schreuder and De Visser (2014) propose that the small EU market for many legumes, for example, may be behind a historical lack of investment, resulting in limited commercial breeding activities, supported by the observations of stakeholders. As mentioned previously, Voisin et al. (2014) and Magrini et al. (2016) posit that a systemic 'lock-in' has developed, favouring cereals whilst side-lining grain legumes. These

systemic problems need addressing for not only traditional EU protein-rich crops, but potentially also for novel crops. The modelling demonstrates the striking potential of quinoa and certain lupin species in many regions of the EU. Research attention should be dedicated to these crops to take advantage of their modelled potential. These crops in tandem with more resilient traditional crops may represent robust, protein-rich meat replacement cropping options for future European agricultural systems, reinforcing previous findings (Ruiz et al., 2014; Lucas et al., 2015).

The findings of this modelling represent the first-step in informing policies to promote protein-rich crops as replacements of animal products in diets and to enable internal food security of EU-based protein production. Geographically differentiated planning, research, and breeding strategies could assist in taking advantage of the positive changes to suitability in northern Europe, while addressing the reductions in southern Europe before they become too extreme. Strategies to achieve these aims could follow those outlined previously. Shifts in agricultural research and development investments towards crops that are likely to be less vulnerable to climate change in given areas could become a priority, following suggestions by Manners and van Etten (2018). Magrini et al. (2016) highlights the historical precedence in research shifts and their success in improving protein-rich crop production in Europe. Increased research could also take advantage of the largely untapped capacity of many protein rich species for adaptation to more stress tolerant forms due to their considerable land-race genetic diversity (Coba de la Peña and Pueyo, 2012; Rastogi and Shukla, 2013; Daryanto et al., 2015). The benefits of increased focussed breeding programmes could be used to address the modelled distribution shifts from this investigation by focussing on identified constraints that may be faced. The long-term benefits from focussing on breeding, may assist in developing more resistant varieties, with subsequent long-term benefits (Cowling et al., 2017; Considine et al., 2017). The projected long-term high prices of plant-proteins (Pilorge and Muel, 2016) and recent expansions in European cultivation (Watson et al., 2017) are likely to make such strategies economically and politically attractive. Further strategies could follow those developed by stakeholders and suggested by the literature including: knowledge and physical infrastructure development (Schreuder and De Visser, 2014), and educational activities (Magrini et al., 2016) to encourage not only production but also consumption, coupled with financial support mechanism (Cullis and Kunert, 2017).

Finally, consideration should also be made of the cultural potential of these crops. The findings stemming from the backcasting exercise infer a currently limited social capacity for wide-scale consumption and production increases of protein-rich crops. The benefits of crop shifting encouraged by climate change, or novel crop introductions, would be lost if there was limited capacity to process, market, or consume them. Therefore, it seems evident that introduction of plant-based meat replacement products would be entirely reliant upon responsive supply and value chains, which according to stakeholders are largely absent in much of the EU. Lucas et al. (2015) recently found that there are sizable issues concerning supply chains. These problems would need to be addressed, with Magrini et al. (2016) identifying the need for downstream industry development to counter these problems. To address this, Manners and van Etten (2018) outline that agricultural research and development investments could be increasingly

moved away from solely focussing upon production, and increasingly shifted towards supply chain development, marketing, and education.

5. CONCLUSIONS

This research has combined index development, mathematical goal programming, trend analysis, participatory assessments, and crop suitability modelling to gain a unique perspective of the socio-economic processes behind land-use changes and potential opportunities for addressing these processes in the future. The findings stemming from this investigation offer a series of outputs that can contribute to improving the knowledge base of the interactions of these processes to better inform future decision-making. In particular, to improve sustainable management of forests, reduce the extent of trade-offs in agriculture-forest systems, outline options for reducing external socio-economic pressures upon forests, and derive potential policy options for achieving the aforementioned. The most relevant of these outputs and contributions, along with the potential of the methodologies applied, their utility to policy-making, and decision-making are outlined below.

5.1 General findings and research contributions

1. The diversity, interconnectedness, and multi-scalar nature of the socio-economic processes associated with deforestation across Latin America highlights the complex nature of deforestation and the difficulty accompanying its analysis from a socio-economic perspective. Despite this, the analysis did suggest the opportunity for aggregation of such factors, to quantify how the amalgamation of these processes in a particular country (or state) may implicitly define the vulnerability of forests to deforestation. Investigation of previous analyses of forest vulnerability emphasised the limited focus on socio-economic vulnerability, in favour of environmental vulnerability. This presented an opportunity to redress this gap in the research with the development of a metric for quantifying (spatially and temporally) forest vulnerability from socio-economic factors and processes.

The Deforestation Vulnerability Index showed small, but widespread reductions in vulnerability across Latin American and Caribbean countries over recent years, 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 reductions. Despite recent improvements in governance across many Amazonian countries the subsequent reduction in vulnerability, implementation of further and more widespread governance reforms, to solidify forest conservation, may be challenging, especially under increasingly turbulent political landscapes. The benefits of institutional reforms may only be reaped in the long-term, by which time governments may have changed and the benefits of change lost for the implementing administration. 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 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 at

various scales. The DVI can also be used in conjunction with other tools/ indices to develop a meta-indice, in turn generating a more refined perspective of forest vulnerability, which could aid in their management and conservation. The index can also be used to direct reactive and responsive sustainable forest management strategies tailored to and considerate of socio-economic vulnerabilities.

2. The novel application of goal programming for the Province of Guarayos (Bolivia), demonstrated the presence of ES trade-offs, which have been widely recorded in other regions of LAC under similar development and agricultural conditions. This model highlighted the antagonistic relationship between achievement of maximising farm income and farm sequestration simultaneously. The model also demonstrated the overt influence of decision-making on these relationships. This modelling was also able to develop and characterise potential management option spaces for different characteristic farm types within the province. Focussing management preferences towards more balanced strategies may provide the most acceptable and achievable management strategy, offering potentially acceptable solutions for income and conservation for the future. The solutions could be implemented to reduce antagonism between farm based agricultural income (and subsequent socio-economic development) and natural resource conservation (through protection of carbon sequestration sinks).

Goal programming also provided further contributions through the demonstration of the potential efficacy of two opposing policy scenarios to reduce the negative impacts of these ES trade-offs. Policy measures addressing this antagonism and the influence of management preferences were found to be effective under extreme management preferences, improving both net farm income and net farm carbon sequestration under certain circumstances, with a policy directed at ecosystem service conservation especially effective at improving both farm-scale income and carbon sequestration. However, governance, financial, and political barriers will need to be further explored as they will likely inhibit the potential of any particular policy to inhibit the extent of these antagonistic relationships between these goals at local scales. A conclusion evident from the DVI, with governance being a fundamental pivot between high and low vulnerability.

Beyond this, this modelling has contributed in its demonstration of the highly complex and antagonistic environment within which contemporary policy makers and decision-makers find themselves in rural regions of Bolivia. These individuals are charged with encouraging rural socio-economic development and simultaneously conserving natural resources, but are constrained by governance and financial limitations. The outcomes of this research suggest that a balance between these goals is often impossible and results in evident losses in forest area and increases in forest vulnerability. In consideration of these circumstances, in situ application of models such as the multi-objective goal programming model may assist in developing more realistic and viable alternative management solutions, to avoid such conflictive states. Application may aid in identifying and developing common attractive solutions amongst stakeholders, whilst formulating a stakeholder dialogue to find a balance between antagonistic objectives. Dialogue establishment could also encourage mutually beneficially social learning

and trust building amongst stakeholders. Dialogue could aid in developing context specific and tailored policy responses, necessary to encourage conservation and limit poverty in tropical forest systems.

3. This research demonstrates that global and continental dietary patterns continue to shift towards greater animal product consumption and production, and increasingly away from consumption of legumes. Despite the environmental and health impacts of animal product consumption, global diets continue to shift towards ever greater reliance upon these products. The implications of these patterns may be stark for future environmental protection, considering the demand for feed products, with forest areas increasingly sacrificed to satiate this demand.

Increased consumption and production of these products, contrary to theorised patterns, continues even in wealthier regions of the world. Across the EU-28, some of the wealthiest countries were those found to be increasing consumption of animal products at the greatest rates. Further, few countries were found to reduce animal product consumption, whilst simultaneously increasing consumption of potential legumes that could potential replace animal proteins. The arguments for the benefits of these consumption shifts, according to this thesis, remain unheeded across much of the EU. This suggests the need for interventions to encourage change.

Stakeholder interactions highlighted an array of barriers and opportunities for consumption and production of legumes across the EU. Implementation of participatory backcasting derived four innovative potential strategies, which working back from a positive future, could form the basis of future (2030) transitions in EU plant-protein production and consumption. These strategies revolved around increased funding for research into protein-rich crops, development and support of local supply chains, consumer education and awareness building, and policy supports. The development of a plant-protein lobby was noted to be key for many strategies.

4. This study represents the first European-scale analysis of the impacts of climate change on many protein-rich crops. The results suggest that current protein-rich crop distributions reflect climatic suitability and suggest widespread under-utilisation and latent potential of many crops across much of the European Union. The results further outline the heterogeneous impacts of climate change upon crop suitability, with northern Europe in general favoured under the conditions of future climates. Non-traditional crops including quinoa and lupin species may present robust crop options under future climates, with traditional crops like chickpea and lentil found to be more sensitive to climatic changes across southern Europe and will likely need to shift northwards.

These findings represent the first-step in informing policies to promote protein-rich crops as replacements of animal products in human diets, whilst enabling internal food security of EU-based protein production. Geographically differentiated planning, research, and breeding strategies could be implemented to take advantage of the positive changes to suitability in northern Europe, whilst addressing the reductions in southern Europe before they become too extreme. Strategies could focus upon shifts in agricultural research and development

investments, knowledge and physical infrastructure development, and educational activities to encourage not only production but also consumption, coupled with financial support mechanism.

5.2 Conclusions on the methodological approach

This research has explored and established the benefits of a novel methodological approach for analysing land-use changes at multiple scales and for parsing out the interactions between these changes and socio-economic processes, as well the role of decision-making in many of these processes. The selection and combination of previously applied methodologies in an innovative manner has provided an enhanced understanding of food production, rural livelihoods, and ecosystem conservation at multiple scales.

The robustness of the multi-scale analysis has also been evidenced through its capacity to incorporate local actors and stakeholders in the research process. The outputs derived from these interactions undoubtedly enhance the findings and aid in legitimising derived policy actions and strategies. Inclusion of stakeholders and the application of approaches that can incorporate them highlight the clear benefits of such analyses when approaching complex process such as land use change.

The relative simplicity of the approaches applied, strengthened by their combination, and their capacity for spatial and temporal expansion outlines the opportunity for transferring and expanding the scope of the analyses performed either individually, or as a whole, when further data or needs arise. The application of this novel methodology has allowed for the identification, testing, and characterisation of potential policy options for the future to address the investigated processes that have implications for land-use changes, as well as for food production, rural livelihoods, and ecosystem conservation. This demonstrates one of the clear benefits of this approach with its capacity to outline policy option spaces that can be used to guide future decision-making in the realm of environmental, agricultural, and rural development policies.

The investigation applied a standardised approach for index development to formulate a composite index of forest vulnerability in Latin America and Caribbean countries. This permitted not only the development of an original metric for quantification of forest vulnerability to socio-economic factors, but included the perspectives of stakeholders and experts in its development. The inclusion of diverse perspectives of forest vulnerability emphasised the differences in opinion concerning the importance of the socio-economic processes driving deforestation, which can be highly dependent upon scale and location. The flexibility of the composite index development was further emphasised through its capacity for quantifying vulnerability at multiple scales. This capacity highlighted the presence of heterogeneity in vulnerability at different scales. The simplicity of this methodology, as well as its flexibility, allows for future inclusion of further variables, new temporal data, and spatial expansion. This flexibility is conducive to providing a more globalised perspective of the vulnerability of forests to socio-economic processes and to deforestation.

The multi-scale application of this index helped to identify sub-national regions with elevated vulnerability. To explore the role of decision-making at more localised scales in one of these examples, multi-objective goal programming was implemented. It was applied to model how differential decision-making outcomes can influence two highly antagonistic goals in agriculture-forest systems. Goal programming emphasised these conflicts, in particular their impacts on ecosystem services. The strength of this approach also permitted the application of policy scenarios to address and improve the identified antagonistic situation. Application of goal programming reinforced its utility for analyses of ecosystem services, its ability to simulate decision-making without direct input from such actors, whilst also providing potential management solutions. This capacity for outlining the option space for management solutions and how this changes under the conditions of distinct policy scenarios, demonstrates the utility of this methodology for use by policy-makers. The methodology applied also lends itself for future in-situ application and spatial expansion of application to gather a more detailed and comparative perspective of the local scale impacts across regions of high deforestation vulnerability.

The combination of trend analyses and participatory assessments allowed for the examination of historical trends, current barriers and opportunities, and future strategies to increase EU plant-protein consumption and production. Stakeholder involvement permitted the inclusion of knowledge from distinct groups, offering novel stakeholder based solutions to address such complex societal problem. Implementation of the backcasting methodology provided an image of a normative future, but also allowed stakeholders to envision how contemporary production and consumption patterns can be altered in a step-wise fashion. It also provided participants with a methodology that removes the restrictions normally associated with analyses of the future, permitting greater creativity in the development of potential strategies. Furthermore, participatory approaches offered an interactive platform for engaging stakeholders, allowing for social learning, consensus building, and providing greater legitimisation of the strategies developed due to the diversity of stakeholders involved.

To address how potential animal replacement products, like protein-rich crops, will respond to future climate change across the European Union, the application of the crop suitability modelling demonstrated its efficacy in providing national scale impacts for these crops across all European Union MS. The implemented model provided a highly resolved (4 km²) analysis of potential future protein-rich crop portfolios suitable for all arable regions of the EU. This highly detailed information represents a step forward in the analysis of climate change impacts in the EU for these generally under researched, but potentially important crops. The benefits of this approach are reinforced by its demonstrated capacity to include other physical attributes within the model (e.g. pH), providing increasingly more reliable outputs of crop suitability and the potential impacts of climate change. This model can be applied, currently, to identify the impacts of climate change and suggest crop portfolios at the landscape-scale. In the future, when more resolved climate data becomes available, these results could be further refined to the farm-scale. The provision of such highly resolved information for farmers and policy makers could

have considerable utility in assisting decision-making and agricultural policy-making, as well as for encouraging research efforts over the coming years.

In conclusion, the application of this methodology has allowed this research to achieve its 6 primary objectives. It has, through the development of the DVI been able to quantify how changes in socio-economic conditions can have notable effects upon forest vulnerability, it also demonstrated how these conditions at different scales can have dramatically different effects upon vulnerability. The investigation has also been able to identify the farm-scale ES trade-offs present in regions of high deforestation vulnerability, with the explicit role and impacts of decision-making on these trade-offs quantified. This thesis also successfully evaluated and updated global, continental, and EU Member States trends in animal product and legume consumption and production. It has also identified barriers and opportunities to consumption and production of plant proteins in the EU, and presented a series of strategies that could form the basis of future transitions towards greater replacement of animal products by legumes and protein-rich crops in future consumption and production landscapes. Finally, this investigation has successfully modelled how such protein-rich crops may be influenced by future climate change across the European Union. From this, the analysis has been able to outline a series of policy suggestions that could be implemented to address these issues.

5.3 Limitations and Further Research

Limitations

In the development of any composite index, such as the DVI, there are always associated problems with treating countries as uniform. The comparison between Chile (a developed and mature economy) and Suriname (a relatively undeveloped and growing economy) is a recognised limitation when considering the socio-economic drivers of deforestation in each country. In the quantification of vulnerability in each country, the omission of indicators which have been previously correlated with deforestation due to: a lack extensive data (e.g. land tenure), them falling outside of the scope of the analysis (e.g. physical characteristics like slope and aspect), or them not being identified also represents a limitation of the outputs of the DVI. Also, the use of generic weighting for indicators across all countries may severely limit the ability of the DVI to fully unpick national and state differences in vulnerability.

The assumptions made in applying the multi-objective goal programming model may be, as with any model, unrealistic in terms of their representation of reality. As part of the goal programming model, farmers were assumed to adhere to legal levels of deforestation. Under present environmental monitoring and political conditions in the region, this is unlikely. Furthermore, the static nature of this model did not allow for the inclusion and analysis of the impacts of market and climate signals. Consideration of such signals may have demonstrated how climate and market changes may drive changes to crop portfolios and the subsequent impacts upon the established trade-off relationship. The assumption that farmers will continue maximising profits following the same crop portfolios is likely misplaced. Under such

circumstances farmers are likely to change crops, introduce new profitable crops, or adopt new management techniques as a means of adaptation to localised climatic changes. The model provides a static snapshot of the antagonistic conditions in the region and the role of decision-making and policy application in driving these conditions. That the model was static may have also have resulted in too much weight having been given to limiting emissions. In the model, hypothetical decision-makers may only consider the immediate impacts on sequestration, without consideration of the long-term financial benefits of deforestation. This in turn may reduce the likelihood of short-termism, where a decision-maker only considers the immediate profitability of reducing sequestration (via deforestation), without considering the potential long-term costs. Therefore, to improve the accuracy and realism of this model it would be beneficial to further develop it, as a dynamic model, offering the opportunity for year on year developments.

The data used for the trend analysis of consumption changes also represents a limitation, mainly concerning the availability and how representative the data are. Under ideal conditions, the development of this trend analysis would have been developed using national food consumption surveys for all analysed countries, across multiple years. The data derived from such surveys would provide reliable and accurate consumption data with which to make detailed analyses and refined conclusions. However, the lack of concrete and standardised methodologies for such surveys, coupled with the limited spatial and temporal coverage due to the associated costs of representative surveys often limits their application and in turn their utility for international multi-year comparative analyses. In response to the scarcity and paucity of representative national and continental scale household survey data, publicly available databanks are the only source of consistent data. The use of open access databanks, are also problematic, in terms of their potential overestimation of consumption and their lack of disaggregated data. Further limitations associated with this analysis are that protein consumption transitions are framed as being from animal products, to legumes. The sources of most non-animal dietary proteins are invariably from cereals. These were purposely excluded to shed a light on legume trends, which could have been shadowed had cereal data been included.

In their current format, the strategies to increase consumption and production of legumes lack detail, with vague milestones and actions outlined. Repetition of the exercise, over an extended workshop(s), allowing for greater detail and validation of results would strengthen the relevance and robustness of these and future results. Further, the outputs of backcasting are normative and therefore could benefit from combination with other analyses to combine the “...*what should happen...*” questions of backcasting, to “...*what will/could happen...*” of other scenario based methods. More generally, stakeholder based approaches, such as backcasting, and ensuing outputs can be inhibited by unrepresentative stakeholders, stakeholder frustration, identification of new conflicts, and further empowerment of important stakeholders to name a few. Consideration of the representative nature of stakeholders is an important factor and may severely limit the validity of any outputs or conclusions drawn from such methodologies.

The biophysical crop-modelling performed is also not without limitations. The limitation of EcoCrop analyses are well recognised. The reliance of the model upon monthly data may mask

high-stress, shorter extreme conditions. This may manifest itself in failure to account for impacts of extreme weather conditions during important physiological steps (flowering and fruiting). This may infer the inability of the model to fully capture all interactions between climatic conditions and physiological development. The implications of this may be that results over-estimate suitability. Furthermore, the parameterisation of the model is based upon the use of ecological niches defined by experts and the literature. These parameters remain to be fully validated. That this study does not perform a detailed calibration of the EcoCrop model for each crop and their parameters is a further limitation. Finally, the outputs from this model are unable to offer indications of any relationship between yields and suitability. This makes cross referencing the results from this analysis to other models and studies, using yield as their reference point, difficult.

Further Research

- The DVI should be applied globally. This expansion could help to clarify whether the identified trends in LAC are continentally specific, or are indicative of global vulnerability trends. Furthermore, such expansion could help to highlight whether vulnerability indicators are globally consistent in terms of their importance.
- The DVI should be continually updated with new data and indicators, when they become available and are identified. This could reduce the potential effects of the indicators omitted (as noted above). The index could also be tested through the development of country specific weighting schemes, which would require country based stakeholder interactions to develop weights.
- The trade-off analysis should be further developed in situ with decision-makers to formulate their own satisficing values and goal preference weighting. This development would provide more realistic and viable alternative management solutions. These advances could also assist in formulating a stakeholder dialogue to find a balance between the two antagonistic development goals.
- The goal programming model could be expanded to become a dynamic (multi-year) model. This expansion could not only address the aforementioned limitations, but could also allow for the inclusion of the impacts of climate change. Development of such a model and inclusion of climate effects would offer a more realistic interpretation of trade-offs and the role of decision-making.
- The trend analyses should be expanded to include cereals and other non-animal based protein sources. Inclusion of these data would allow for a more reliable and refined analysis of whether animal-plant protein transitions are evident.
- The analysis of national consumption and production spatial patterns could be extended globally. This analysis could be used to contextualise the European Union scale results and may demonstrate whether EU Member States are outliers or the rule in terms of

richer regions largely failing to enter the proposed transition towards less consumption of animal products.

- Further and more extended backcasting based workshops should be developed to provide greater detail and validation of initial results, while strengthening their relevance and robustness. This workshop(s) could provide more detailed information concerning timelines, actions, and milestones for the transitional pathways from a more diverse group of stakeholders and representation of Member States.
- The EcoCrop model should be calibrated against genebank accession coordinates to provide a more resolved understanding of the impacts of climate change in Europe. Expert validation of the ecological niche parameters for each crop should also be considered to further improve the reliability of the model outputs. Expert-based validation could also be used to define ranges for parameters not currently included in the model (i.e. soil fertility), further refining the suitability outputs. Experts could also be used to define parameter ranges for neglected and under-utilised species, not currently present within the EcoCrop database.
- Another logical next step for the model is to expand it spatially (globally) and temporally (2070s), whilst also comparing outputs across various representative concentration pathways (RCPs) to provide a range of potential outcomes.

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7. ANNEXES

Annex 1. Latin American and Caribbean forest area and forest area changes from 1990-2014

Country	Forest Area 1000 ha						Annual Change					
							1990 2000		2000-2014		1990-2014	
	1990	1995	2000	2005	2010	2014	1000 ha/yr	%	1000 ha/yr	%	1000 ha/yr	%
Anguilla	6	6	6	6	6	6	0	0	0	0	0	0
Antigua and Barbuda	10	10	10	10	10	10	0	-0.3	0	-0.1	0	-0.2
Argentina	34793	33327	31860	30186	28596	27409	-293.3	-0.8	-317.9	-1	-307.7	-0.9
Aruba	0	0	0	0	0	0	0	0	0	0	0	0
Bahamas	515	515	515	515	515	515	0	0	0	0	0	0
Barbados	6	6	6	6	6	6	0	0	0	0	0	0
Belize	1616	1538	1459	1417	1391	1371	-15.7	-1	-6.3	-0.4	-10.2	-0.6
Bermuda	1	1	1	1	1	1	0	0	0	0	0	0
Bolivia	62795	61443	60091	58734	56209	55053	-270.4	-0.4	-359.9	-0.6	-322.6	-0.5
Brazil	546705	533990	521274	506734	498458	494522	-2543.1	-0.5	-1910.9	-0.4	-2174.3	-0.4
British Virgin Islands	4	4	4	4	4	4	0	-0.1	0	-0.1	0	-0.1
Cayman Islands	13	13	13	13	13	13	0	0	0	0	0	0
Chile	15263	15549	15834	16042	16231	17434	57.1	0.4	114.3	0.7	90.5	0.6
Colombia	64417	63108	61798	60201	58635	58528	-261.9	-0.4	-233.6	-0.4	-245.4	-0.4
Costa Rica	2564	2470	2376	2491	2605	2726	-18.8	-0.7	25	1.1	6.7	0.3
Cuba	2058	2247	2435	2697	2932	3146	37.7	1.8	50.8	2.1	45.4	2.2
Dominica	50	49	47	46	45	44	-0.3	-0.5	-0.3	-0.6	-0.3	-0.5
Dominican Republic	1105	1296	1486	1652	1817	1950	38.1	3.4	33.1	2.2	35.2	3.2
Ecuador	14631	14180	13729	13335	12942	12627	-90.2	-0.6	-78.7	-0.6	-83.5	-0.6
El Salvador	377	355	332	309	287	269	-4.5	-1.2	-4.5	-1.3	-4.5	-1.2
French Guiana	8218	8200	8182	8168	8138	8132	-3.6	0	-3.6	0	-3.6	0
Grenada	17	17	17	17	17	17	0	0	0	0	0	0
Guadeloupe	74	74	74	74	73	73	0	0	-0.1	-0.1	-0.1	-0.1
Guatemala	4748	4478	4208	3938	3722	3576	-54	-1.1	-45.1	-1.1	-48.8	-1
Guyana	16660	16641	16622	16602	16576	16536	-3.8	0	-6.1	0	-5.2	0

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Haiti	116	113	109	105	101	98	-0.7	-0.6	-0.8	-0.7	-0.8	-0.7
Honduras	8136	7264	6392	5792	5192	4712	-174.4	-2.1	-120	-1.9	-142.7	-1.8
Jamaica	345	343	341	339	337	336	-0.4	-0.1	-0.4	-0.1	-0.4	-0.1
Martinique	49	49	49	49	49	49	0	0	0	0	0	0
Mexico	69760	68808	67856	67083	66498	66132	-190.4	-0.3	-123.2	-0.2	-151.2	-0.2
Montserrat	4	3	3	3	3	3	-0.1	-2.9	0	0	0	-1.2
Netherlands Antilles (former)	1	1	1	1	1	1	0	0	0	0	0	0
Nicaragua	4514	4164	3814	3464	3114	3114	-70	-1.6	-50	-1.3	-58.3	-1.3
Panama	5040	4954	4867	4782	4699	4633	-17.3	-0.3	-16.7	-0.3	-16.9	-0.3
Paraguay	21157	20263	19368	18475	16950	15648	-178.9	-0.8	-265.7	-1.4	-229.5	-1.1
Peru	77921	77034	76147	75528	74811	74141	-177.4	-0.2	-143.3	-0.2	-157.5	-0.2
Puerto Rico	287	369	450	463	479	493	16.3	5.7	3	0.7	8.6	3
Saint Kitts and Nevis	11	11	11	11	11	11	0	0	0	0	0	0
Saint Lucia	22	22	21	21	21	20	-0.1	-0.3	-0.1	-0.3	-0.1	-0.3
Saint Pierre and Miquelon	3	3	3	3	3	3	0	-0.6	0	-0.8	0	-0.7
Saint Vincent and the Grenadines	25	26	26	26	27	27	0.1	0.4	0.1	0.3	0.1	0.3
Suriname	15430	15411	15391	15371	15351	15336	-3.9	0	-3.9	0	-3.9	0
Trinidad and Tobago	241	237	234	230	226	233	-0.7	-0.3	-0.1	0	-0.3	-0.1
Turks and Caicos Islands	34	34	34	34	34	34	0	0	0	0	0	0
United States Virgin Islands	24	22	20	19	18	18	-0.3	-1.3	-0.2	-1	-0.2	-1
Uruguay	798	1084	1370	1522	1731	1822	57.2	7.2	32.3	2.4	42.7	5.4
Venezuela (Bolivarian Republic of)	52026	50589	49151	47713	47505	46847	-287.5	-0.6	-164.5	-0.3	-215.8	-0.4

Annex 2. Latin American and Caribbean arable area and arable area changes from 1990-2014

Country	Arable Area 1000 ha						Annual Change					
	1990	1995	2000	2005	2010	2014	1990-2000		2000-2014		1990-2014	
							1000 ha/yr	%	1000 ha/yr	%	1000 ha/yr	%
Anguilla	0	0	0	0	0	0	0		0		0	
Antigua and Barbuda	4	4	4	4	4	4	0	0	0	0	0	0
Argentina	26575	27105	27640	32898	37981	39200	106.5	0.4	825.7	3	526	2
Aruba	2	2	2	2	2	2	0	0	0	0	0	0
Bahamas	8	6	7	7	9	8	-0.1	-1.3	0.1	1	0	0
Barbados	16	16	15	13	12	11	-0.1	-0.6	-0.3	-1.9	-0.2	-1.3
Belize	52	62	64	70	75	78	1.2	2.3	1	1.6	1.1	2.1
Bermuda	0	0	0	0	0	0	0	3.3	0	-1.8	0	0
Bolivia (Plurinational State of)	2100	2600	3144	3806	4297	4473	104.4	5	94.9	3	98.9	4.7
Brazil	50681	58059	57776	69157	70363	80017	709.5	1.4	1588.6	2.7	1222.3	2.4
British Virgin Islands	2	2	1	1	1	1	-0.1	-5	0	0	0	-2.1
Cayman Islands	0	0	0	0	0	0	0	0	0	0	0	0
Chile	2802	2120	1750	1450	1271	1289	-105.2	-3.8	-32.9	-1.9	-63	-2.2
Colombia	3305	2399	2818	2026	1763	1675	-48.7	-1.5	-81.6	-2.9	-67.9	-2.1
Costa Rica	260	220	210	210	225	232	-5	-1.9	1.6	0.8	-1.2	-0.4
Cuba	3391	3684	3504	3672	3384	3088	11.3	0.3	-29.7	-0.8	-12.6	-0.4
Dominica	5	3	5	5	6	6	0	0	0.1	1.4	0	0.8
Dominican Republic	900	930	898	820	800	800	-0.2	0	-7	-0.8	-4.2	-0.5
Ecuador	1604	1574	1616	1296	1186	1018	1.2	0.1	-42.7	-2.6	-24.4	-1.5
El Salvador	550	582	650	702	673	750	10	1.8	7.1	1.1	8.3	1.5
French Guiana	10	10	12	12	12	13	0.2	2	0.1	0.7	0.1	1.3
Grenada	2	1	1	2	3	3	-0.1	-5	0.1	14.3	0	2.1
Guadeloupe	21	21	19	19	21	22	-0.2	-1	0.2	1.2	0.1	0.3
Guatemala	1300	1355	1395	1400	1196	934	9.5	0.7	-32.9	-2.4	-15.3	-1.2
Guyana	480	480	450	420	420	420	-3	-0.6	-2.1	-0.5	-2.5	-0.5
Haiti	780	800	900	900	1100	1070	12	1.5	12.1	1.3	12.1	1.5
Honduras	1462	1600	1068	1050	1020	1020	-39.4	-2.7	-3.4	-0.3	-18.4	-1.3
Jamaica	119	158	140	128	120	120	2.1	1.8	-1.4	-1	0	0

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Martinique	10	8	11	10	10	10	0.1	1	-0.1	-0.6	0	0
Mexico	21709	22560	22905	23296	23507	22993	119.6	0.6	6.3	0	53.5	0.2
Montserrat	2	2	2	2	2	2	0	0	0	0	0	0
Netherlands Antilles (former)	8	8	8	8	8	8	0	0	0	0	0	0
Nicaragua	1300	1650	1917	2000	1531	1504	61.7	4.7	-29.5	-1.5	8.5	0.7
Panama	499	500	548	548	569	563	4.9	1	1.1	0.2	2.7	0.5
Paraguay	2110	2600	3020	3460	4145	4800	91	4.3	127.1	4.2	112.1	5.3
Peru	3500	3740	4410	3930	4085	4152	91	2.6	-18.5	-0.4	27.2	0.8
Puerto Rico	65	33	60	66	57	61	-0.5	-0.8	0.1	0.2	-0.2	-0.3
Saint Kitts and Nevis	8	7	7	4	5	5	-0.1	-1.3	-0.1	-2	-0.1	-1.6
Saint Lucia	3	2	2	2	3	3	-0.1	-3.1	0.1	3.6	0	0.1
Saint Pierre and Miquelon	3	3	3	3	3	2	0	0	-0.1	-2.4	0	-1.4
Saint Vincent and the Grenadines	4	5	5	5	5	5	0.1	2.5	0	0	0	1
Suriname	57	57	57	49	55	65	0	0	0.6	1	0.3	0.6
Trinidad and Tobago	36	40	35	25	25	25	-0.1	-0.3	-0.7	-2	-0.5	-1.3
Turks and Caicos Islands	1	1	1	1	1	1	0	0	0	0	0	0
United States Virgin Islands	4	3	2	2	1	1	-0.2	-5	-0.1	-3.6	-0.1	-3.1
Uruguay	1241	1306	1373	1392	2033	2411	13.2	1.1	74.1	5.4	48.7	3.9
Venezuela (Bolivarian Republic of)	2832	2581	2595	2655	2700	2700	-23.7	-0.8	7.5	0.3	-5.5	-0.2

Annex 3. Latin American and Caribbean meadows and grasslands area and area changes from 1990-2014

Country	Permanent Meadows and Grasslands Area 1000 ha						Annual Change					
	1990	1995	2000	2005	2010	2014	1990-2000		2000-2014		1990-2014	
							1000 ha/yr	%	1000 ha/yr	%	1000 ha/yr	%
Anguilla	0	0	0	0	0	0	0		0		0	
Antigua and Barbuda	4	4	4	4	4	4	0	0	0	0	0	0
Argentina	99970	99920	99870	103900	108500	108500	-10	0	616.4	0.6	355.4	0.4
Aruba	0	0	0	0	0	0	0		0		0	
Bahamas	2	2	2	2	2	2	0	0	0	0	0	0
Barbados	2	2	2	2	2	2	0	0	0	0	0	0
Belize	49	50	50	50	50	50	0.1	0.2	0	0	0	0.1
Bermuda	0	0	0	0	0	0	0		0		0	
Bolivia (Plurinational State of)	33200	33835	33831	32957	33000	33000	63.1	0.2	-59.4	-0.2	-8.3	0
Brazil	184200	192972	196206	196000	196000	196000	1200.6	0.7	-14.7	0	491.7	0.3
British Virgin Islands	5	5	5	5	5	5	0	0	0	0	0	0
Cayman Islands	2	2	2	2	2	2	0	0	0	0	0	0
Chile	12850	12930	13000	14000	14015	14015	15	0.1	72.5	0.6	48.5	0.4
Colombia	40083	40083	40314	38944	39150	41365	23.1	0.1	75.1	0.2	53.4	0.1
Costa Rica	1795	1538	1350	1315	1279	1265	-44.5	-2.5	-6.1	-0.4	-22.1	-1.2
Cuba	2900	2500	2500	2540	2657	2764	-40	-1.4	18.9	0.8	-5.7	-0.2
Dominica	2	2	2	2	2	2	0	0	0	0	0	0
Dominican Republic	1200	1200	1197	1197	1197	1197	-0.3	0	0	0	-0.1	0
Ecuador	4921	5107	5087	4990	4920	3123	16.6	0.3	-140.3	-2.8	-74.9	-1.5
El Salvador	600	600	600	636	637	637	0	0	2.6	0.4	1.5	0.3
French Guiana	9	11	7	7	9	12	-0.2	-2.2	0.4	5.3	0.1	1.5
Grenada	1	1	1	1	1	1	0	0	0	0	0	0
Guadeloupe	24	25	24	21	35	28	0	0	0.3	1	0.1	0.6
Guatemala	2500	2602	2500	2321	1796	1799	0	0	-50.1	-2	-29.2	-1.2
Guyana	1230	1230	1230	1230	1230	1230	0	0	0	0	0	0
Haiti	497	490	490	490	490	490	-0.7	-0.1	0	0	-0.3	-0.1
Honduras	1500	1530	1508	1700	1760	1760	0.8	0.1	18	1.2	10.8	0.7

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Jamaica	257	229	229	229	229	229	-2.8	-1.1	0	0	-1.2	-0.5
Martinique	19	12	12	10	20	15	-0.7	-3.7	0.2	1.7	-0.2	-0.9
Mexico	81364	81243	80952	80667	80547	81035	-41.2	-0.1	5.9	0	-13.7	0
Montserrat	1	1	1	1	1	1	0	0	0	0	0	0
Netherlands Antilles (former)	0	0	0	0	0	0	0		0		0	
Nicaragua	2530	2683	2990	3016	3200	3275	46	1.8	20.4	0.7	31	1.2
Panama	1470	1477	1535	1522	1509	1509	6.5	0.4	-1.9	-0.1	1.6	0.1
Paraguay	14960	13773	17215	16380	17000	17000	225.5	1.5	-15.4	-0.1	85	0.6
Peru	17916	17387	17802	18216	18631	18800	-11.4	-0.1	71.3	0.4	36.8	0.2
Puerto Rico	320	232	146	98	87	87	-17.5	-5.5	-4.2	-2.9	-9.7	-3
Saint Kitts and Nevis	2	2	2	1	1	1	0	0	-0.1	-3.9	0	-2.3
Saint Lucia	2	2	1	1	1	1	-0.1	-3.5	-0.1	-3.8	-0.1	-2.9
Saint Pierre and Miquelon	0	0	0	0	0	0	0		0		0	
Saint Vincent and the Grenadines	2	2	2	2	2	2	0	0	0	0	0	0
Suriname	20	21	21	18	17	17	0.1	0.5	-0.3	-1.3	-0.1	-0.6
Trinidad and Tobago	6	6	7	7	7	7	0.1	1.7	0	0	0	0.7
Turks and Caicos Islands	0	0	0	0	0	0	0		0		0	
United States Virgin Islands	5	4	4	3	2	2	-0.1	-2	-0.1	-3.6	-0.1	-2.5
Uruguay	13631	13587	13543	13400	12362	12000	-8.8	-0.1	-110.2	-0.8	-68	-0.5
Venezuela (Bolivarian Republic of)	18250	18240	18240	18240	18200	18200	-1	0	-2.9	0	-2.1	0

Annex 4. List of the 30 Global Circulation Models used within the analysis. Associated institute and country included.

Model	Institute	Country
BCC_CSM 1.1 (m)	Beijing Climate Center	China
BCC_CSM 1.1	Beijing Climate Center	China
BNU_ESM	Beijing Normal University	China
CCMA_CANESM2	Canadian Centre for Climate Modelling and Analysis	Canada
CESM1_BGC	University Corporation for Atmospheric Research/National Center for Atmospheric Research	USA
CESM1_CAM5	University Corporation for Atmospheric Research/National Center for Atmospheric Research	USA
CSIRO_ACCESS1.0	Commonwealth Scientific and Industrial Research Organisation	Australia
CSIRO_ACCESS1.3	Commonwealth Scientific and Industrial Research Organisation	Australia
CSIRO_MK3_6_0	Commonwealth Scientific and Industrial Research Organisation	Australia
FIO_ESM	The First Institute of Oceanography	China
GFDL_CM3	Geophysical Fluid Dynamics Laboratory	USA
GFDL_ESM2G	Geophysical Fluid Dynamics Laboratory	USA
GFDL_ESM2M	Geophysical Fluid Dynamics Laboratory	USA
GISS_E2_H_CC	Goddard Institute for Space Sciences	USA
GISS_E2_R_CC	Goddard Institute for Space Sciences	USA
GISS_E2_R	Goddard Institute for Space Sciences	USA
INM_CM4	Institute for Numerical Mathematics	Russia
IPSL_CM5A_LR	Institut Pierre-Simon Laplace	France
IPSL_CM5A_MR	Institut Pierre-Simon Laplace	France
LASG_FGOALS_G2	Institute of Atmospheric Physics, Chinese Academy of Science	China
MIROC_ESM_CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute, and National Institute for Environmental Studies	Japan
MIROC_ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute, and National Institute for Environmental Studies	Japan
MIROC_MIROC5	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute, and National Institute for Environmental Studies	Japan
MOHC_HADGEM2_CC	Met Office Hadley Centre	UK
MOHC_HADGEM2_ES	Met Office Hadley Centre and Instituto Nacional de Pesquisas Espaciais	UK and Brazil
MPI_ESM_LR	Max Planck Institute for Meteorology	Germany
MRI_CGCM3	Meteorological Research Institute	Japan
NCAR_CCSM4	National Center for Atmospheric Research	USA
NCC_NORES1_M	Norwegian Climate Centre	Norway
NIMR_HADGEM2_AO	National Institute of Meteorological Research/ Korea Meteorological Administration	South Korea

Annex 5. Deforestation Vulnerability Index results under expert weighting. Index results have been rounded to two decimal points, whilst % percentage change was calculated on non-rounded values.

Deforestation Vulnerability Index				
	2000	2005	2010	% Change 2000-2010
Argentina	0.31	0.44	0.40	29.5
Belize	0.41	0.42	0.41	0.4
Bolivia	0.42	0.50	0.41	-4.1
Brazil	0.41	0.46	0.38	-5.7
Chile	0.21	0.21	0.12	-43.5
Colombia	0.40	0.44	0.37	-9.1
Costa Rica	0.31	0.37	0.35	12.9
Cuba	0.39	0.35	0.32	-17.6
Dominican Republic	0.43	0.49	0.40	-6.3
Ecuador	0.44	0.47	0.41	-7.3
El Salvador	0.41	0.48	0.36	-13.2
Guatemala	0.48	0.54	0.43	-10.9
Guyana	0.35	0.38	0.37	5.6
Haiti	0.60	0.66	0.62	3.5
Honduras	0.44	0.52	0.45	1.5
Jamaica	0.39	0.44	0.37	-3.9
Mexico	0.31	0.33	0.31	-2.3
Nicaragua	0.49	0.50	0.42	-14.7
Panama	0.34	0.37	0.28	-18.4
Paraguay	0.53	0.49	0.54	2.1
Peru	0.37	0.42	0.33	-11.8
Suriname	0.38	0.29	0.38	0.8
Uruguay	0.22	0.29	0.19	-15.9
Venezuela, RB	0.40	0.48	0.41	1.5

Annex 6. Deforestation Vulnerability Index results from provincial application. Results from both expert and stakeholder weighting displayed.

Deforestation Vulnerability Index		
	Expert Weight	Stakeholder Weight
Bolivia	0.39	0.55
Santa Cruz	0.54	0.73
Brazil	0.36	0.39
Para	0.42	0.43
Mexico	0.27	0.28
Jalisco	0.33	0.36

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Annex 7. Results from pairwise t-test analysis of Deforestation Vulnerability Index (DVI) values under random weighting of DVI indicators through Monte Carlo analysis.

Note: Values represent p values from pairwise t-test using data for the year 2010. Significance codes used in place of values for highly significant results. ISO two letter country codes used

	AR	BZ	BO	BR	CL	CO	CR	CU	DO	EC	SV	GT	GY	HT	HN	JM	MX	NI	PA	PY	PE	SR	UY	VE
AR																								
BZ	***																							
BO	***	0.69																						
BR	0.1	***	***																					
CL	***	***	***	***																				
CO	***	***	***	***	***																			
CR	***	***	***	***	***	***																		
CU	***	***	***	***	***	***	***																	
DO	***	0.06.	0.13	***	***	***	***	***																
EC	***	0.002**	0.01**	***	***	***	***	***	0.27															
SV	***	***	***	***	***	0.26	***	***	***	***														
GT	***	***	***	***	***	***	***	***	***	***	***													
GY	***	***	***	***	***	0.003**	***	***	***	***	0.07.	***												
HT	***	***	***	***	***	***	***	***	***	***	***	***	***											
HN	***	***	***	***	***	***	***	***	***	***	***	***	***	***										
JM	***	***	***	***	***	0.04*	***	***	***	***	0.002*	***	***	***	***									
MX	***	***	***	***	***	***	***	0.16	***	***	***	***	***	***	***	***								
NI	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***							
PA	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***						
PY	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***					
PE	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***				
SR	***	***	***	***	***	***	***	***	***	***	0.02*	***	0.66	***	***	***	***	***	***	***	***			
UY	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***		
VE	***	***	***	***	***	***	***	***	0.01*	0.15	***	***	***	***	***	***	***	***	***	***	***	***	***	

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Annex 8. Average percentage suitability changes for all crops across EU-28 countries. Percentage changes calculated from baseline suitability (1970-2000) and future climatic scenario data (2050).

Note: Values represent average change, with standard deviation in brackets. Values generated from running the extended EcoCrop model for each of the 30 GCMs under RCP4.5. National values generated as a mean suitability value calculated from all suitability values within national boundaries where agriculture was practiced.

	AT	BE	BG	CZ	CY	DE	DK	EE	EL	ES	FI	FR	HR	IE	HU	IT	LT	LU	LV	NL	PL	PT	RO	SE	SI	SK	UK
Amaranth	11.2 (14.9)	0.2 (18.1)	-5.8 (31.8)	-3.7 (23.2)	-7.5 (25.5)	-0.4 (24.9)	22.7 (30.6)	15.3 (23.1)	7.7 (13.5)	-0.6 (17.7)	23.2 (22.6)	-1.5 (15.7)	-0.2 (9.8)	5.8 (13.5)	-5.1 (35.6)	1.1 (10)	8.1 (21.3)	-2.1 (20.6)	10.3 (20.6)	5.6 (20.3)	2 (26.8)	-2 (17.6)	-2.7 (25)	13.6 (25)	-1.2 (10)	-2.1 (19.7)	7.4 (18.9)
Andean Lupin	89.6 (43.6)	61.7 (32.7)	-6.7 (42.7)	215.1 (127.8)	-6.9 (16.6)	100.2 (48.4)	4.2 (1.9)		8.7 (13.5)	1.3 (20.4)		39 (18.4)	36.6 (17.4)	65 (32)	25.4 (38.4)	27 (11.9)	2.3 (1.3)	89.7 (46.8)		102.6 (47.2)	210.9 (140)	-11.1 (17.7)	30.5 (62.9)	159.2 (140.1)	58.2 (24.8)	82.2 (46.5)	85.4 (41.4)
Blue Lupin	-19.3 (13.6)	-18.9 (13.4)	140.3 (282)	5.8 (46.7)	-15.3 (21.4)	-15.1 (22.2)	15.6 (25.5)	62.3 (57.8)	-5.3 (10.7)	-23.5 (17)	154.5 (103.5)	-24.7 (15.2)	-29 (10.1)	-1.7 (2.1)	-24.4 (68.9)	-17.9 (8.9)	10.1 (45.8)	-27.2 (13.4)	-1.6 (32.9)	-15.8 (10.5)	31.5 (89)	-16.3 (20.6)	-0.5 (59.9)	51.6 (66.6)	-31.5 (9)	-24 (26)	5.7 (41.8)
Buckwheat	20 (38.3)	63.8 (261.1)		48.9 (160.8)	68.3 (85.4)	36.2 (103.9)			17 (23.7)	10.4 (31)		37.6 (61.2)	31.4 (45)	64.6 (72.7)		14.6 (37.8)					13.6 (69.7)	14.9 (47.5)	175.2 (293.5)		-0.6 (34.8)	12.2 (55.4)	62.4 (71.7)
Chickpea	22.1 (20.6)	-0.1 (22)	13.9 (124.1)	26.8 (68.9)	4.2 (40)	12.3 (39.5)	22.3 (37.5)	35.1 (42.6)	13.7 (17.6)	-5.5 (20.1)	68.4 (47.2)	-12 (24.6)	-1.9 (12.3)	1.5 (10)	5.9 (77.3)	-1.3 (14.1)	16.1 (35.3)	-5.8 (22.7)	17.9 (33.3)	9 (25.3)	76 (102.8)	-6.2 (24.4)	47.2 (106)	28.7 (45.6)	2.2 (5.2)	16 (42.9)	6.7 (23.1)
Common Bean	36.8 (22.3)		13.8 (124)	26.5 (61.6)	5.1 (42.3)	14.7 (39.6)	19.7 (36)	32.9 (44.1)	8.3 (16.3)	-5.7 (19.8)	146.3 (87.4)	-15.2 (24.4)	-2.7 (12.4)	17.8 (13.1)	6.4 (77.5)	-2.8 (13.8)	19.2 (37.8)	-5.1 (24.4)	18.2 (35.4)	3.2 (22.5)	72.1 (99.1)	-5.1 (23)	46.7 (103.1)	26.2 (41.2)	8 (5.9)	22.4 (40.8)	20.9 (28.5)
Cowpea	76 (45)	16 (90.2)		268.6 (412.7)	84.1 (115.8)	66 (132.4)	54.2 (132.3)	38.5 (59)	38.9 (31.4)	-7 (29.3)		-8.6 (64.2)	10.5 (24.7)	33.6 (34.7)	98.1 (222.5)	7.4 (31.4)	140.4 (222.4)	-1.4 (100)	1.3 (1.9)	89.2 (181.9)	0.8 (1.6)	29.8 (54.7)	1.3 (2.1)	100.5 (187.9)	38.5 (16.3)	169.2 (187.2)	89.4 (87.2)
Faba Bean	23.2 (16.7)	-0.3 (15.7)	-23.4 (41.4)	11 (36.8)	-8.3 (29.1)	7.6 (26.9)	12.2 (25.3)	19.9 (25.3)	5.6 (14.5)	-4.9 (17.9)	74.9 (29)	-8.4 (16.6)	-0.4 (10.6)	2.6 (8.3)	-11.9 (41.2)	-0.8 (10.5)	9.9 (22.5)	-4.5 (16.7)	11.5 (21.4)	6.1 (17.7)	26.2 (42.7)	-5.9 (18.1)	8 (47.1)	11.6 (21.7)	10.7 (7.3)	8.8 (26.3)	6.4 (17.1)
Lentil	24.1 (17.1)		-23.4 (41.4)	11.8 (38)	-7.7 (27.6)	7.8 (27.9)	15.9 (26.8)	21 (25.6)	6 (14.5)	-4.8 (18)	82 (33.7)	-7.3 (16.9)	-1.7 (9.9)	2.7 (9.5)	-11.9 (41.2)	-0.9 (10.5)	10.6 (22.7)	-4.1 (18.2)	12.5 (21.9)	7.1 (20.1)	27.1 (44)	-6.8 (18.5)	8.6 (47.6)	13 (23.3)	4.1 (4.9)	9.9 (27.1)	7.3 (18)
Pea	16.2 (28.4)	19.4 (103.3)		29 (126.6)	19 (50.5)	27.1 (90.1)	59.2 (116.3)	3.1 (4.2)	5.6 (17.7)	3.6 (24.6)	111.9 (164.4)	19.8 (52.5)	-0.2 (19.2)	24 (30.1)	21 (138.8)	3.1 (25.9)	131.8 (173.7)	15.9 (135.7)	0.7 (0.9)	127.9 (219.8)	60.2 (166.6)	6.4 (40.1)	76.8 (184.6)	103.7 (199.8)	-3.9 (16.6)	8.7 (52.9)	24 (38)
Quinoa	9.9 (13.9)	-1.9 (11.9)		21.7 (35.1)	-12.9 (59.6)	8.8 (13.4)	18.2 (26.8)		-8.6 (18.8)	-18.4 (14.9)		-11 (7.5)	-16.8 (9.1)	16.4 (10.7)	30.5 (172.5)	-14.5 (8.6)	36.8 (55.2)	-5.4 (15.8)		179.1 (985)	18 (28.1)	-10 (31.3)	247.4 (133.5)	9.2 (12.3)	-13.9 (11.6)	11 (24.3)	11.4 (15.7)
Soybean	87.1 (54.2)	29.5 (181.2)		0.3 (0.4)	0.2 (0.2)	124.5 (239.4)	0.9 (1.4)		55.7 (38.2)	-2.5 (31.9)		6.9 (82.2)	10.7 (31.6)	37.6 (50.5)	49.1 (81.6)	17.5 (38.9)	6.2 (9)	87.1 (398)		41.1 (109.2)	0.9 (2)	62.3 (81.2)	8.7 (18.3)	0.4 (0.7)	38.8 (18.9)	0.3 (0.3)	92.4 (94.2)
White Lupin	34.6 (22.6)	3.1 (19.9)	1.3 (2.1)	69.3 (108.5)	1.4 (29.7)	26 (48.4)	46.2 (48.9)	127 (104.9)	5.4 (15.3)	-10.8 (18.1)	282.8 (198.9)	-13.5 (30.4)	2.6 (14)	19.7 (11.2)	23.3 (119.7)	-1.4 (12.4)	51.2 (71.3)	2.2 (25.3)	19.7 (46.4)	5.4 (19.4)	107.9 (183.9)	-5.4 (25.5)	42.3 (125.4)	91.6 (112.3)	16.2 (8.2)	17.2 (50.4)	28 (34.9)