D2.6: CASE STUDY SCALING SCENARIO FINAL REPORT

INPUT FOR SIMULATION MODELLING OF SCALING LAND-BASED MITIGATION SOLUTIONS IN THE LANDMARC CASE STUDY COUNTRIES

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LANDMARC

Land-use based Mitigation for Resilient Climate Pathways

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Changes with respect to the DoA	*Deliverable was submitted with four months delay according to the Grant Agreement. CINEA project advisor was informed about this delay (with justification).*
Dissemination and uptake	*This deliverable provides an overview of qualitative information per country on the realistic scaling potential of one or more land-based mitigation solutions (LMT portfolios) in a series of LANDMARC case study countries (including Germany, The Netherlands, Portugal, Spain, Sweden, Switzerland, Ukraine, Burkina Faso, Kenya, South Africa, Indonesia, Nepal, Vietnam, Canada, and Venezuela).* *This qualitative information serves as input for simulation modelling done with the following models: DayCent (time series biogeochemical model), ALCES (web-based land use change simulation model), LandSHIFT (global / regional land use change simulation model), E3ME (macro-econometric model)*

Short Summary of results

This document provides an overview of qualitative information that has been collected for the assessment of the scaling potential of national LMT portfolios in the respective case study countries. The qualitative information has been collected via literature review and a range of stakeholder engagement activities (e.g., interviews, workshops). The qualitative information has been synthesised or codified in more structured tables as a first step to translate or codify the qualitative information into inputs relevant for the scenario modelling within the LANDMARC project. These results feed into two upcoming deliverables (October 2023).

- D5.3 Model run outputs from model set (e.g., DayCent, ALCES, LandSHIFT, and FaBIO)
- D5.5 E3ME model simulations

Evidence of accomplishment

This report.

Preface

Negative emission solutions are expected to play a pivotal role in future climate actions and net zero emissions policy scenarios. To date most climate actions have focussed on phasing out fossil fuels and reducing greenhouse gas emissions in, for example, industry, electricity, and transport. While zero emission trajectories in these sectors will remain a priority for decades to come, it is expected that residual GHG emissions will remain. To be able to fulfil the Paris Agreement and meet the world's climate goals research, policy and markets are increasingly looking at negative emission solutions.

This is why the nineteen LANDMARC consortium partners work together to:

- Estimate the climate impact of land-based negative emission solutions, in agriculture, forestry, and other land-use sectors,
- Assess the potential for regional and global upscaling of negative emission solutions,
- Map their potential environmental, economic, and social co-benefits and trade-offs,

LANDMARC is an interdisciplinary consortium with expertise from ecology, engineering, climate sciences, global carbon cycle, soil sciences, satellite earth observation sciences, agronomy, economics, social sciences, and business. There is a balanced representation of partners from academia, SMEs, and NGOs from the EU, Africa, Asia, and the Americas, which ensures a wide coverage of LMTs operating in different contexts (e.g., climates, land-use practices, socio-economic etc.) and spatial scales.

The LANDMARC project consortium:

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Purpose of this document

This document provides an overview of qualitative information (literature review and stakeholder engagement) that has been collected by the LANDMARC country case study partners for the assessment of the realistic scaling potential of national portfolios of land-based mitigation solutions (LMTs). This qualitative information is presented in the form of ***narratives*** or ***storylines*** (see Annex II), as well as a series of tables in which an effort has been made to translate or codify the qualitative information into inputs to be used in simulation modelling (see **Annex III**).

Chapter **1** introduces the methodological approach the LANDMARC research team has taken to co-design and/or co-create scaling scenarios for both individual land-based mitigation solutions (LMTs), and LMT portfolios within the respective (#14) countries. Chapter **1** also provides an overview of the simulation model suite applied within LANDMARC, as well provides a rationale for co-creation of scaling scenarios with local (national) level stakeholders.

Chapter **2** provides an overview table of the availability of qualitative narratives / storylines per country, and the application of simulation models to the respective LMT or LMTs per country. The descriptive section in Chapter **2** provides a condensed overview of the main development trajectories or scenarios to be used for simulation modelling derived from **Annex III.**

Chapter **3** provides a more cross-cutting or thematic synthesis of all national LMT narratives / storylines for all 14 LANDMARC case study countries where simulation modelling will be applied (see **Annex II**).

1. Introduction

In this Chapter we briefly discuss some of the concepts (Sections **1.1** and **1.2**), simulation modelling tools (Section **1.3**) and the methodological approach (Section **1.4**) the LANDMARC research team has taken to co-create scenarios scaling up the implementation of individual land-based mitigation solutions (LMTs) as well as LMT portfolios (Section **1.5**) within (#14) LANDMARC case study countries.

1.1 Narratives, storylines, or scenarios?

Within this interdisciplinary research project (LANDMARC), researchers from different cultural and scientific backgrounds (e.g., simulation modelling, social, and natural sciences) are collaborating to create new knowledge and insights. With respect to advancing our common understanding of the impacts of scaling portfolios of land-based mitigation technologies and practices (LMTs)[1] there has been ample debate and sometimes confusion with respect to the proper use of terminology for simulation modelling. Are we talking about development scenarios, narratives, or storylines?

Within LANDMARC we follow the logic of a ***'storyline approach'***, such as stressed by (Shepherd, T.G., Boyd, E., Calel, R.A. et al., 2018). They propose an alternative approach to represent uncertainty in the physical aspects of climate change simulation modelling. Within the 'storyline' approach there is more *"emphasis on qualitative understanding rather than quantitative precision."* This more qualitative approach highlights the existing limitations of probabilistic approaches used in climate change simulation modelling. While some authors (Shepherd, T.G., Boyd, E., Calel, R.A. et al., 2018) mainly refer to climate change scenarios based on simulation modelling, the logic for a storyline approach also applies to other types of simulation modelling, where increasing complexity such as portfolio-option based approaches can be developed.

1.2 Stakeholder engagement & co-creation

A more qualitative approach to the elicitation and creation of possible future scenarios also has merit in other fields of simulation modelling, aside from earth systems modelling (ESM). In the field of transition scenario studies, economic and land-use modelling - which study the impacts on and from human or socio-economic systems on the environment - the codified, technocratic, and/or stylized (i.e., quantitative) approaches to scenario design often can hamper effective and meaningful engagement/participation, and co-creation of plausible futures, particularly with non-expert stakeholders.

For example, (Faehn, T. and Stoknes, PE, 2023) suggest that: *"involving a relatively broad transdisciplinary stakeholder group [… can] be extremely rewarding in the first, explorative phase of the [scenario design process]"*, while in the second phase i.e., the translation of the qualitative

[1] e.g., afforestation, agroforestry, peatland rewetting, no tillage, crop-/grassland management, biochar, BECCS

narratives into quantitatively modelled scenarios (or pathways), stakeholders with more *"specialised technical skills, training within economic and technological numerical modelling and insight"* would be needed.

This report is the product of a series of stakeholder engagement activities carried out in 14 LANDMARC case study countries[2], complemented with literature review to advance our qualitative understanding of the key factors (drivers, and constraints) and dynamics of implementing a range (portfolios) of LMTs nationwide (i.e., scaling) within each country. This work has been conducted by the LANDMARC country case study partners, with great support from many local and indigenous stakeholders (e.g., local communities, farmers, land/forest owners or managers, investors, AFOLU sector advisors, companies, local, and national policy makers, researchers) who have shared their views and perspectives via interviews, follow-up information exchanges, focus groups, and workshops. Thus, while the storylines (or narratives) are written and edited by the respective LANDMARC country case study leaders, they are an attempt to reflect the combined, and shared knowledge and information gathered throughout the research process and (at the time of writing) still ongoing stakeholder engagement activities.[3]

1.3 Simulation modelling

Within the LANDMARC project simulation modelling is pursued with the following five models:

1. **DayCent:** DayCent is a daily time series biogeochemical model used in agroecosystems to simulates fluxes of carbon and nitrogen between the atmosphere, vegetation, and soil. Model inputs include daily maximum/minimum air temperature and precipitation, surface soil texture class, and land cover/use data. Model outputs include daily fluxes of various N-gas species (e.g., N_2O, NO_X, N_2); daily CO_2 flux from heterotrophic soil respiration; soil organic C and N; net primary productivity; daily water and nitrate (NO3) leaching, and other ecosystem parameters. DayCent has been tested with data from various native and managed systems.

[2] Germany, The Netherlands, Portugal, Spain, Sweden, Switzerland, Ukraine, Burkina Faso, Kenya, Indonesia, Nepal, Vietnam, Canada, Venezuela.

[3] Special effort has been put on ensuring that the stakeholder engagement process within the LANDMARC project was sufficiently inclusive, and that all relevant perspectives (e.g., minorities, gender and indigenous) are represented. However, despite these efforts, we acknowledge that specific (inter)national events (e.g., political instability, recession, COVID-19), as well as our own limitations (time and resources) unintentionally may have resulted in an imperfect engagement / participatory process and representation.

We strongly encourage those (research) projects, policy makers, companies and communities that seek to make use of the results of the LANDMARC project to build upon and strive for a more inclusive and representative engagement process.

It is our shared belief that a (global, national, local) transition without adequate participation and representation will not be effective (i.e., resulting in low acceptance and low speed of implementation). This transition process already starts in the exploratory stages of research into plausible / feasible futures.

2. **LandSHIFT:** LandSHIFT (Land Simulation to Harmonize and Integrate Freshwater Availability and the Terrestrial Environment) is a land use change model for global and regional scale simulation experiments. its principal objective is to simulate the interactions of socio-economic drivers and the biophysical environment determining land use and land use changes and to assess the impacts of these changes on human society and the environment. The model design aims at delivering a tool that can play a central role in scenario analysis projects.
3. **E3ME:** The E3ME model is a macro-econometric model with global coverage designed to address major economic and economy-environment policy challenges. E3ME features integrated treatment of the world's economies, energy systems, emissions, and material demand. This enables it to capture two-way linkages and feedbacks between these components. The model is characterized by a high level of disaggregation, enabling detailed analysis of sectoral and country-level effects in global analysis.
4. **ALCES:** The ALCES software creates cumulative effect models that simulates changes in landscape composition and related indicators in response to LMTs and other drivers, such as natural disturbances and climate change. ALCES will be communicating scenario outcomes via web-based dashboards made of dynamics maps and graphs. This tool also has the capacity for comprehensive simulation of co-benefits as is required for trade-off analysis across case-studies.
5. **FaBIO:** FABio (Forestry and Agriculture Biomass Model) is a simulation model created using the method of system dynamics and agent-based modelling of biomass production and use in agriculture and forestry and describes their impact on certain environmental indicators.

1.4 Translating storylines into model inputs

Throughout the co-design process LANDMARCs' country case study leaders have gone through the four following basic steps:

1. Literature review eliciting a long-list of land-based mitigation technologies and practices that can be scaled in the respective country,
2. Stakeholder elicitation (often interview) based shortlisting of LMTs that are deemed most relevant or promising by stakeholders,
3. Creation of qualitative storylines (narratives) of LMT portfolios gathering complementary information from different sources (literature, stakeholders),
4. Generating national LMT scaling scenarios portfolios (based on storylines) to serve as input for simulation modelling.

Both step one [**1**] and two [**2**] focussed on narrowing down the scope of the research activities, to a) limit it to manageable levels, and b) ensure a high level of relevance. With respect to identifying the most 'relevant' or 'promising' LMTs for a given country we did not developed a prescribed set of selection technocratic or quantifiable criteria, such as e.g., technical scaling potential, or lowest cost option, lowest land claim and/or most favourable public acceptance. We intentionally left the shortlisting of LMTs up to the specific LANDMARC researcher who was informed by stakeholders and ongoing (public and political) debates and other developments within the respective country. While this may have created in a certain bias for some LMTs, we believe that LMT prioritization of the specific focus of low-carbon transition research should build more on stakeholder (society, or community) driven or participatory decision-making approaches (i.e., is not only the privilege of researchers). Moreover, the creation and prescription of a set of measurable criteria by researchers for selection may just as easily have created certain biases.

The drafting of the qualitative storylines [**3**] has gone through several iterations or revisions. The country reports (see **Annex II**) are the final product of these iterations.[4]

The final step in this process [**4**] was to make a first effort to translate these qualitative storylines into more quantified scenarios that could be used in simulation modelling. One of the main challenges here was to generate or extract key values, numbers and/or parameters from the storylines that would be fitting or matching with key model input parameters and assumptions.

Continued dialogue and information exchange between the modelling experts and country case study leaders in the project has shown that it is challenging to standardize and harmonize this process. For instance, to make it fully transparent and objective given the different characteristics of the selected LMTs and LMT portfolios, as well as specific country context (e.g., differing socio-economic drivers/constraints and dynamics). To address this inter- and transdisciplinary challenge, the iterative dialogue between modelling experts and country case study leaders, as well as engaged external national stakeholders has resulted in the development of a guide to enable the codification of storylines into input for scenario simulation modelling (see. **Annex I** 'A stepwise approach to generate LMT scenarios including input for LANDMARC model simulations'). This guide was developed by J. Onigkeit, M. Laub and J. Lieu.

1.5 Modelling LMT portfolios

Simulation models traditionally, have been used to explore the magnitude of specific socio-economic and/or environmental impacts associated with introducing a new technology or practice into an existing system (e.g., ecosystem, economic system, social system). For example, energy transition studies have benefited from using simulation models to explore for example the (integrated) impacts, co-benefits, trade-offs of scaling e.g., solar PV systems, bioenergy systems and/or phasing out nuclear or coal fired power generation systems. Also, in the area of land-based mitigation technologies and

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[4] Initial, and draft versions of these storylines were developed within the context of the LANDMARC project and have been part of the following project specific outputs:

- Milestone 6: Initial draft report with national scaling scenarios
- Deliverable 2.1: Case study scaling scenario advanced DRAFT report

These two outputs have not been circulated publicly, to prevent spreading and using of different versions of a similar document. The two previous versions in combination with this new 'final' version reflect the changes of ongoing co-creation and subsequent improvements in the storylines. Follow-up co-creation actions, and dynamic developments could build upon these storylines and further refine and develop them as the collective knowledge and perspectives evolve.

practices there has been an accumulation of studies focussing on assessing the impacts of scaling specific LMT practices such as agroforestry, afforestation, BECCS deployment, or a regional roll-out of biochar plants and application.

While it is scientifically appealing to perform '*ceteris paribus*' simulation modelling for a single technology or practice, real-world transitions (e.g., energy, bioeconomy, circular economy, mobility, industry) are increasingly facing the (un)expected consequences of the aggregated impacts of different actions, measures or events that are implemented in parallel or occur at the same time. To reach net zero by 2050 rapid deployment and scale up of a wide portfolio of mitigation (reduction) and carbon dioxide removal measures will be required in roughly the next three decades.

With respect to the assessing the impacts of implementation of land-based mitigation technologies (LMTs), negative emission technologies (NETs) or carbon dioxide removal (CDRs) solutions, there is a need for more integrated or holistic simulation modelling approaches that capture the dynamics of implementing a suite or 'portfolio' of mitigating measures. For example, realistic future scaling scenarios for afforestation, are only viable if proper account has been given for the future scaling of BECCS and/or biochar. Similarly, with respect to the usage of land and biomass, BECCS and biochar – in principle – are two competing (or alternative) solutions for producing renewable energy and delivering permanent carbon dioxide removals.

Portfolio-based simulation modelling approaches are expected to increase in importance, in areas of land-use, economic, and climate modelling (e.g., IAMs, ESMs). The inability to adequately represent (i.e., to model) may increasingly become a limitation for providing robust and actionable evidence-based support for policy makers, decision makers and communities in relation to the transition towards a more sustainable, net-zero economy and society. We need to improve models to consider:

a) specific mitigation and/or removal solutions (e.g., LMTs, NETs, and/or CDRs) or full options-portfolios,[5]
b) the dynamics of interlinkages (i.e., synergetic vs. conflicting or symbiotic vs. parasitic), between different options within a portfolio,
c) or deliver more regionally and spatially explicit assessment results useful for decision makers at the local or regional scale/level[6]

[5] Within LANDMARC regional/global simulation modelling efforts for LMT scaling are pursued. The combinations of simulation models used (i.e., LandSHIFT-G, and EC-Earth3-GCM) do not (yet) allow for inclusion of specific LMT solutions. For this reason, the focus is put on a more limited portfolio with 5 LMTs, including: afforestation, no/reduced tillage, agroforestry, enhanced irrigation and BECCS.

[6] Ongoing EU-funded research projects such as the RESCUE project (link) focus on integrated assessment and earth systems (IAM/ESM) modelling of expanded CDR portfolios. Current IAM/ESM simulation modelling efforts typically include a relatively limited set of CDRs (e.g., mainly BECCS, DACCS, biochar, forest management and afforestation) and/or do not (yet) provide regionally/spatially disaggregated simulation results.

The coupled model systems that are currently used make a probabilistic approach informed by stakeholders (e.g., local knowledge and experience) less and less practical. The sheer (technical) complexity of such systems and the specific parameters and values required as modelling input may eventually alienate and frustrate many non-expert stakeholder groups. Here, qualitative and storyline-based approaches can capture more than one specific option and include a broader portfolio of options. This inclusion of a wider portfolio may help to keep relevant stakeholders actively engaged in the co-creation process. By putting more emphasis on co-creating a more qualitative, holistic/integrated understanding of scaling different LMT portfolios, the fundamental drivers, and constraints will become more apparent to broader stakeholder groups. Such a participatory co-creation processes (provided it is sufficiently inclusive and representative) may eventually foster the creating of a shared vision and belief upon which to act.

2. Overview of results from translating storylines into model inputs

As indicated in Section **1.4** the LANDMARC country case study leaders were requested to synthesise or translate the information from their national LMT portfolio narratives (see **Annex II**) in a specific table format (see **Annex I**). The results of this 'translation' per country are presented in **Annex III**. In this section we provide an aggregated overview (Section **2.1**) and brief discussion (Section **2.2**) on key development and scaling trajectories for LMTs for each country.

2.1 Overview

Table 1 provides an overview of the application of different LANDMARC simulation models (see Section **1.3**) per country and per LMT. Some of the LANDMARC case study countries have provided a storyline for a larger LMT portfolio (e.g., The Netherlands, Spain), while others have focussed on a more limited set of LMTs (e.g., Germany Venezuela).

In most cases the DayCent simulation modelling is linked to one (or two) specific LMTs and is not used to derive results for a full LMT portfolio. FaBIO simulation modelling is only applied to one specific LMT in the German country case study.[7] The LandSHIFT simulation model is also applied in a more limited set of case study countries, but in most cases targets the full national LMT portfolio (i.e., Switzerland, Burkina Faso, Indonesia, and possibly Ukraine[8]). Both the E3ME and ALCES simulation models generally aim to capture the economic or land use change dynamics / impacts of full national LMT portfolios, but more limited coverage of LMTs may also be possible.

Table 1 provides an overview of the (planned, executed) application of all LANDMARC simulation models and their linkage to a respective case study country and LMTs/LMT portfolio. **Annex II** and **Annex III** provide resp. the qualitative input to serve as a starting point for simulation modelling, as well as full descriptions of the national LMT portfolio narratives.

Table 1 also shows which country-LMTs are not yet included in simulation modelling. The respective qualitative information on these LMTs provided in **Annex II** and **Annex III** can also be used by third parties (e.g., other research projects, simulation modelling teams):

- to build on and further develop their own storylines for LMT scaling in a respective country and/or
- to perform their own LMT portfolio model simulations

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[7] The FaBIO simulation model is not part of the original model set in LANDMARC but was applied as a result of stakeholder collaborations and synergies for the German case study.

[8] The decision to deploy LandSHIFT and ALCES simulation modelling in Ukraine is still pending and will depend on the availability of (external) funding.

Country	LMT portfolios	DayCent	E3ME	LandSHIFT	ALCES	FABio
Germany	Forest management		X			X
	Afforestation					
	Soil carbon – mineral soils					
	Soil carbon – organic soils					
Netherlands	Afforestation		X		X	
	Agroforestry	X	X		X	
	Peatland rewetting		X		X	
	BECCS (manure AD-based CCS)		X			
Portugal	Cropland management					
	Pastures (Montados)	(X)				
	Agroforestry (Montados)	(X)				
	Forest management					
Spain	Forest management				X	
	Afforestation / reforestation	X			X	
	Agrosilvopastoral land (Dehesas)				X	
	Grassland management				X	
Sweden	Forest management					
	Afforestation / reforestation					
	BECCS		X			
	Biochar		X			
Switzerland	Agroforestry		X	X	X	
	Organic agriculture	X	X	(X)	X	
	Reduced / no tillage	X	X	X	X	
	BECCS					
	Biochar					
Ukraine	Agroforestry (shelterbelts)			X	X	
	Organic farming	X		(X)	X	
	Reduced / no tillage	X		X	X	
	Bioenergy			(X)		
Burkina Faso	Agroforestry	(X)		X	X	
	Cropland management			(X)	(X)	
	Forest management	X		(X)	(X)	
	Afforestation / reforestation			X	X	
Kenya	Afforestation					
	Agroforestry					
	Integrated soil fertility	X				
South Africa[9]	N.A.					
Indonesia	Reforestation			X	X	
	Peatland management			(X)	X	
	Agroforestry			X	X	
	Soil carbon (biogas & compost)		X			
	Cropland management			(X)	X	
Nepal	Forest management				(X)	
	Afforestation / reforestation				X	
	Agroforestry				X	
	Organic farming				X	
	Improved rice management				X	
Vietnam	Agroforestry				X	
	Biochar (coffee husks)					
	Afforestation / reforestation				X	
Canada	Afforestation		X		(X)	

	Wetland restoration		**X**		**(X)**	
Venezuela	Forest management (integrated	**(X)**			**X**	

Table 1: Overview of LMT portfolios and (intended) application of simulation models per country.

X *= more detailed application of the simulation model indicates higher quality, reliability of the data information used, and more robust co-design approach applied for respective LMT.*

(X) *= less detailed application of the simulation model indicates lower quality, reliability of the data information used, and less robust co-design approach applied for respective LMT.*

- The DayCent simulation modelling partner within LANDMARC is ETH Zürich (ETHZ)[10]
- The E3ME simulation modelling partner within LANDMARC is Cambridge Econometrics (CE)
- The LandSHIFT simulation modelling partner within LANDMARC is University of Kassel (UNIK)
- The ALCES simulation modelling partners within LANDMARC are TU Delft (TUD) and ALCES

2.2 Description

2.2.1 Germany

The German LMT portfolio with developed (qualitative) storylines includes four LMTs, including i) forest management, ii) afforestation, iii) soil carbon enhancement in mineral soils, and iv) soil carbon enhancement in organic soils (peat/wetlands). Simulation modelling with the FaBIO and E3ME model will be applied to forest management.

The key storyline trajectories developed by the country case study leader (Oeko Institute) covers three alternative development or deployment scenarios for all LMTs. The *reference scenario* is geared towards supporting regenerative and restoration practices, while at the same time few additional restrictions are put on continuation of existing economic activities, such as agriculture on organic soils or the continued use of existing managed forests for wood supply. The second and third scenario are resp. labelled as *'achieve existing targets'* and *'green supreme'*. Both scenarios combine the reference scenario with additional (policy) limitations by taking forest area and agricultural soils out of production and reduce livestock (dairy/meat) production to free up land for alternative uses. The key difference is that that the second scenario seeks for compliance with existing climate and environmental targets, while the third scenario works with more ambitious targets.

By limiting the scope of existing economic activities in the AFOLU sectors in Germany, complementary support schemes, revenue streams and business models for farmers and forest owners will need to be in place to support a more radical transition.

[9] The South African case study is solely serving LANDMARC research on improving the earth observation practices for better monitoring of the carbon cycle. Hence, this EO-specific case study is not included in any (qualitative) storyline development or simulation modelling with ALCES, E3ME, LandSHIFT and/or DayCent. More information on this case study can be found here (link) or here (link).

[10] Additional DayCent modelling runs will be performed for non-LANDMARC case study sites, in France, and Australia.

2.2.2 The Netherlands

The Dutch LMT portfolio with developed (qualitative) storylines includes four LMTs, including i) afforestation, ii) agroforestry, iii) peatland rewetting, and iv) CO_2 capture applied to biogas production facilities based on anaerobic digestion of liquid animal manure. Simulation modelling with both the E3ME and ALCES model will be applied to the full LMT portfolio.

The key storyline trajectories developed by the country case study leaders (JIN Climate & Sustainability and Bioclear Earth) covers three alternative development scenarios for all LMTs, which are closely linked to the future scale/size of the Dutch livestock sector (mainly dairy cattle and pig farming).

The *base case* assumes a business-as-usual scenario where the existing (intensive) livestock farming practices, with associated land use, economic benefits and socio-environmental costs remains roughly at current levels. Although this scenario, is incompatible with a range of environmental and climate policy targets the political process and public debate appears to be at an impasse. Two alternative transition scenarios are considered. The first one considers a significant forced reduction of the size of the livestock sector thereby freeing up land for scaling of the more nature based LMTs, such as agroforestry, peatland rewetting and afforestation. The second alternative scenario envisages a more moderate (forced) reduction or buy-out of a share of the livestock farmers, which is combined with the upscaling of biogas production based on anaerobic digestion of (remaining) liquid animal manure. The biogas production facilities can enable the replacement of fossil energy as well as deliver organic fertilizers (to replace chemical fertilizers) and capture biogenic CO_2 (from biogas treatment) which can be stored underground or used in other applications (e.g., food industry).

By limiting existing livestock farming activities in agriculture in The Netherlands, complementary support schemes, revenue streams and new business models for farmers will be needed to be in place to support a more radical transition. Currently, the economic outlook for farmers for the nature based as well as the engineered transition scenario is uncertain / risky. There may be a case for a hybrid transition scenario, where both the nature-based and the engineered LMT scenario co-exist, but are tailored to fit local (e.g., soil, climatic, environmental, and socio-economic) conditions.

2.2.3 Portugal

The Portuguese LMT portfolio with developed (qualitative) storylines includes four nature based LMTs, including i) forest management, ii) agroforestry (Montados), iii) pastures (Montados) and iv) cropland management. Simulation modelling with DayCent will be applied the montados system (combination of agroforestry and grassland pastures).

The key storyline trajectories developed by the country case study leader (AgroInsider) for forest management and agroforestry covers two alternative development scenarios. The *reference scenario* is aiming to maintain the current situation which is assuming it will lead to further degradation of natural capital i.e., ongoing losses in biodiversity and soil/forest degradation and lower resilience and vitality of ecosystems. The alternative development scenario assumes an upgrading of the valuation of natural capital and ecosystems. For this to manifest significant additional amounts of external public and or private finance (e.g., via the voluntary carbon markets) would be required to make the overall ecosystems and local communities more resilient. For cropland and grassland management only one future development trajectory is indicated. For cropland management sustainable agricultural practices through precision farming to conserve soil health and water are 'prescribed'. Similarly, biodiverse pastures rich in legumes and grasses are 'prescribed' as the single future development trajectory. Both development trajectories appear to suggest that regenerative and biodiversity promoting grass- and cropland management can almost be seen as a minimum condition ('conditionality') to be able to sustain some form of productive plant and livestock farming in Portugal under expected future climate conditions.

2.2.4 Spain

The Spanish LMT portfolio with developed (qualitative) storylines includes four nature based LMTs, including i) agrosilvopastoral land management (Dehesas), ii) grassland management, iii) forest management, and iv) afforestation / reforestation of degraded agricultural areas. Simulation modelling with the DayCent will only be applied to afforestation/reforestation, while ALCES simulation model will be applied to the full LMT portfolio.

The key storyline trajectories developed by the country case study leader (Ambienta) covers three alternative development or deployment scenarios for all LMTs. The *reference scenario* is geared towards maintaining some sort of status quo or conservation with respect of the management and use of agricultural, semi-natural, natural and forest land. The two alternative development trajectories present both a positive and negative development scenario. The negative development scenarios for all four LMTs are closely linked to the ongoing depopulation of Spanish rural areas. Linked to that decline is a relatively poor economic outlook and development for rural populations, that will leave more and more land unmanaged, which may give rise to increasing desertification and wildfires. The alternative (positive) development scenario aims to create more favourable socio-economic conditions for rural populations, which can help mitigate the negative effects of climate change on the landscapes, improve ecosystem services driven by better economic outlook for rural populations.

By promoting additional (economic and eco-system service) activities in the rural areas, the landscape management systems can be improved, providing a range of potential co-benefits. This, however, will require a fundamental shift in rural and economic development policies.

2.2.5 Sweden

The Swedish LMT portfolio with developed (qualitative) storylines includes two engineered LMTs, including i) BECCS, and ii) biochar as well as afforestation and forest management. Simulation modelling with the E3ME simulation model will be applied to BECCS and biochar.

The key storyline trajectories developed by the country case study leader (SEI) covers a 'low cost' and a 'high cost' development scenario for both engineered LMTs. The low-cost scenario will result in a higher deployment rate of BECCS and biochar, which is based on assumption of relatively low biomass, and energy prices as well as low costs for CO_2 transport and underground CO_2 storage. The high-cost scenario reflects the reverse, where overall system costs are higher than anticipated.

To fund, or incentivise these LMTs, a mixture of private and public schemes (e.g., voluntary carbon market) is considered, where the low-cost scenario considers ambitious carbon pricing and other complementary policies.

2.2.6 Switzerland

The Swiss LMT portfolio with developed (qualitative) storylines includes three nature based LMTs, including i) organic agriculture (soil carbon), ii) reduced / no tillage, and iii) agroforestry. Simulation modelling with DayCent will be applied to both soil carbon enhancement oriented LMTs (organic agriculture and reduced / no tillage). In addition, both (ALCES and LandSHIFT) as well as the E3ME simulation model will be applied to the full Swiss LMT portfolio.

The key storyline trajectories developed by the country case study leader (ETH Zürich) covers three development trajectories for all LMTs, where the reference scenarios assume a continuation of current practices (or status quo) in terms of land use and agricultural practices. The two alternative development trajectories for the LMT portfolio consider a moderate scaling as well as an ambitious scaling trajectory.

To understand the potential magnitude or impact of scaling these LMTs nationwide, for example by 2050 almost no conventional tillage practices would remain, and about 50% of the permanent grasslands would be under silvopastoral management (agroforestry). For such ambitious development (or scaling trajectories) robust incentive schemes and policies would need to be in place.

2.2.7 Ukraine

The Ukrainian LMT portfolio with consists out of three nature based LMTs, including i) organic farming, ii) reduced / no tillage, and iii) agroforestry. In addition, one engineered LMT, bioenergy (biogas from agricultural feedstocks) is considered. More detailed qualitative storylines/narratives for Ukraine are not available as Ukraine was added as a country case study at a later stage during the LANDMARC research process. Simulation modelling with DayCent will target organic farming and reduced / no tillage, whereas both ALCES and LandSHIFT simulation is intended to be applied to all three nature based LMTs.[11]

The key storyline trajectory developed by the country case study leaders (TUD / ISSAR) covers a ‘balanced mix’ approach where implementation of all four LMTs at a certain scale is deemed most desirable. However, depending on the specific LMT this scenario the specific ambitions differ and for each LMT a high, mid, and low deployment scenario is made. No/reduced tillage practices would have

[11] The implementation of simulation modelling with ALCES and LandSHIFT is dependent on complementary (external) funding.

to be scaled nationwide to reach 13-50% or arable land by 2050, as well as substantial agricultural area would have to be under organic farming management and about 5-15% of arable land needs to be converted into shelterbelts (agroforestry). Also, for biogas developments the ambitions are significant (1,5 – 3,5 bcm m^3 of biomethane) and should be feasible given the much larger technical potential for scaling.[12]

2.2.8 Burkina Faso

The Burkinese LMT portfolio with developed (qualitative) storylines includes four nature based LMTs, including i) agroforestry, ii) cropland management (soil carbon), iii) forest management, and iv) afforestation / reforestation. Simulation modelling with DayCent will be applied to forest management and agroforestry, while efforts will be made to apply ALCES and LandSHIFT modelling to the full LMT portfolio[13].

The key storyline trajectories developed by the country case study leader (eLEAF) covers three development trajectories for all LMTs, where the reference scenarios assume a business-as-usual (or stay as current) development in terms of land use (forest and agricultural practices). The two alternative development trajectories for the LMT portfolio consider a moderate scaling (slow growth) as well as an ambitious (max growth) scaling trajectory.

To understand the potential magnitude or impact of scaling these LMTs nationwide, for example by 2050 almost all farms would have to deploy organic cropland management practices and all forest areas are protected and sustainably managed. In addition, a resp. 70% (2030) and 150% (2050) growth of land under agroforestry management is applied, and a 5% (2030) and 15% (2050) increase of forest cover would have been achieved. For such ambitious development (or scaling trajectories) robust incentive schemes, capacity building, policies, and (inter)national support would need to be in place.

2.2.9 Kenya

The Kenyan LMT portfolio with developed (qualitative) storylines includes three nature based LMTs, including i) afforestation, ii) agroforestry, and iii) integrated soil fertility management (ISFM). Simulation modelling with DayCent will be applied to ISFM.

For Kenya, a range of ISFM scenarios for DayCent simulations have been co-developed with stakeholders compared to the baseline (no/little input) during a workshop. These scenarios are the use

[12] Outside the scope of the LANDMARC project, a small research project has been set up between Ukrainian (Institute for Soil Science and Agrochemistry Research, and Adverio Engineering UA) and Dutch (JIN Climate & Sustainability and Adverio Engineering NL) partners to assess different development scenarios for biogas development and deployment in Ukraine, post-war. The small project, titled: **"Post-war recovery and energy independence strategy through biogas deployment in Ukrainian agriculture"** is funded via a small grant from the TPM (Technology, Policy, and Management) faculty, Energy Transitions Lab from TU Delft.

[13] Cropland management (organic farming) and forest management may be incorporated in the LandSHIFT modelling with less detail due to data and resource limitations.

of organic inputs (farmyard or green manure) at medium or high (1 or 2 t C ha-1 yr-1) or the use of mineral N only (at 30, 60 or 90 kg N ha-1) and the combined use, i.e., real "integrated" soil fertility management at medium and high rates. The simulations will thus effectively cover an option space for farmers at different levels of resource availability.

Annex II provides the qualitative storylines for the Kenyan LMT portfolio. Since, only DayCent simulation modelling will be applied in Kenya no specific input table for simulation modelling (see **Annex III**) for Kenya has been made.

2.2.10 Indonesia

The Indonesian LMT portfolio with developed (qualitative) storylines includes four nature based LMTs, including i) afforestation, ii) agroforestry, iii) peatland management, and iv) cropland management and one engineered LMT targeting soil caron enhancement, namely the deployment of small-scale anaerobic digesters for biogas production and compost/organic fertilizer production. Simulation modelling with ALCES, LandSHIFT will focus on all four nature based LMTs, while E3ME simulation modelling will be applied to biogas and compost systems to enhance soil carbon.

The key storyline trajectories developed by the country case study leader (Su-re.Co) covers two development trajectories for all LMTs. Both a 'High' and 'Low' ambition scenario is considered for all LMTs, where the low ambition scenario generally aims for compliance with existing targets or current efforts, predominantly relying on domestic regulations, internal enforcement and monitoring and funding sources. A key generic conditional for the high ambition scenarios for all LMTs is that more external sources of international funding, capacity building and support are assumed to be needed.

2.2.11 Nepal

The Nepalese LMT portfolio with developed (qualitative) storylines includes five nature based LMTs, including i) forest management, ii) afforestation, iii) agroforestry, iv) organic farming, and v) improved rice management. Simulation modelling with ALCES will be applied to the full LMT portfolio.

The key storyline trajectories developed by the country case study leader (SPRU) covers three development trajectories for all LMTs. The reference scenario assumes limited or partial growth of more sustainable land management practices (all five LMTs). The two alternative development trajectories present resp. a moderate and ambitious scale up of these LMT practices.

Simulation modelling with ALCES, may reveal any potential conflicts in terms of land use. On top of that the proposed development trajectories may have certain co-benefits in terms of reduced usage (and imports) of chemical fertilizers, revitalization of degraded lands, biodiversity, and climate resilience gains. Potential trade-offs could entail a lower level and productivity of domestic food supplies. Proposed development trajectories suggest a strong reliance on national subsidies and regulations. However, some international funding support may be required to support the transition and dampen possible increases in domestic food prices.

2.2.12 Vietnam

The Vietnamese LMT portfolio with developed (qualitative) storylines includes three LMTs, including i) agroforestry, ii) biochar (from coffee husks), and iii) afforestation/reforestation. Simulation modelling with ALCES will be applied to the upscaling of agroforestry practices and afforestation / reforestation.

The key storyline trajectories developed by the country case study leader (CIAT) covers two development trajectories for agroforestry and two for biochar. Agroforestry scaling is assumed to result either in a conversion of 50% or nearly all current monocropping systems. For biochar scaling either half or all the coffee wastes are converted into biochar. However, for the second scenario two varieties are designed, where the end use market differs (i.e., biochar for export market as activated carbon or biochar for domestic use for soil application).

Simulation modelling with ALCES, may reveal any potential conflicts in terms of land use. The proposed development trajectories suggest a strong reliance on national subsidies and regulations.

2.2.13 Canada

The Canadian LMT portfolio with developed (qualitative) storylines includes two nature based LMTs, including i) afforestation, and ii) wetland restoration. Simulation modelling with ALCES and E3ME will be applied to the full LMT portfolio.

The key storyline trajectories developed by the country case study leaders (TUD & Innolab) covers three development trajectories for all LMTs. The reference scenario assumes limited (minimal compliance) efforts made by logging and oil and gas industries with respect to land reclamation practices in relation to cutlines and wetlands. This scenario would allow continuation of such economic practices with minimal compliance land reclamation practices. The second development trajectory would entail the protection / conservation of most remaining natural landscapes and aim for a moderate or limited restoration of affected landscapes. The third development trajectory is the most ambitious with almost all wetland under conservation/restoration practices and all cutlines fully restored.

Simulation modelling with ALCES, may reveal any potential conflicts in terms of land use in areas where afforestation / reforestation and/or rewetting may occur (or could be combined). E3ME simulation modelling could provide insights in the overall economic impact on the oil and gas and timber industries.

2.2.14 Venezuela

The Venezuelan LMT portfolio with developed (qualitative) storylines includes one main nature based LMTs, namely Integrated fire management (IFM). This LMT builds strongly upon indigenous knowledge and populations with respect to forest fire management. Simulation modelling with DayCent is considered and modelling with ALCES will be applied.

The key storyline trajectories developed by the country case study leaders (COBRA) covers three development trajectories IFM. The reference scenario assumes that traditional/indigenous fire management practices remain prohibited, while modern fire management strategies do not prevent the periodic megafires (fuel accumulation). The other two development trajectories consider resp. a limited and high level of acceptance and scaling of indigenous IFM. The limited scaling of IFM is a result of a weak policy framework and low enforcement, whereas the high level of IFM scaling considers a more robust, nationwide policy, enforcement, and funding framework for forest conservation and IFM.

Simulation modelling with ALCES, may reveal any differences in impacts on landscapes and effectiveness of forest fire management under (currently banned) indigenous practices versus conventional or regulated forest fire management.

3. Synthesis of national LMT portfolio storylines / narratives

This chapter synthesises all 14 national LMT portfolio storylines by elaborating on some common cross-cutting themes. This will allow the reader to achieve a contextualized understanding of the main topics addressed in the Case Study Country LMT portfolio storyline documents presented in **Annex II.**

3.1 Land use

Land use plays a critical role in developing scaling up trajectories, as most (nature based) LMTs involve some form of change in land use. While local ecosystems have the potential to accommodate some LMTs, their implementation must comply with regional land use constraints, such as high population density, food (or other resources) security, or limited usable land due to alpine or desert/degraded landscapes. When there is intense competition for land, techniques that are less land-intensive or can be combined (e.g., agroforestry) are given priority.

For instance, in Switzerland, where most land is either urbanized, dedicated to intensive farming, protected forests (with already high carbon stocks), or alpine, BECCS and biochar are the preferred LMTs since they can be applied without significant domestic land use competition (biomass can be imported). However, these two techniques compete for biomass, and it must be considered that their combined mitigation potential is not the sum of their individual potential. These LMTs can be combined by applying BECCS to the production of biochar, increasing the mitigation potential without significantly increasing land competition. However, if BECCS must be applied through the production of domestic biomass not derived from residues, it could lead to increased land competition.

From a land use perspective, agroforestry can be understood a form of combined land use which could alleviate land use competition, as observed in Kenya and Switzerland scenarios. However, agroforestry still needs to comply with food and income security as its implementation can result in significant yield decreases.

Land use changes are expected to face more competition in most countries due to population growth and the further implementation of often land-intensive renewable energy, with some countries facing more specific challenges in food and energy security, as expressed by Germany. Sanctions on Russia following the war in Ukraine have increased the demand for locally produced food and energy, further intensifying land competition by the widespread implementation of renewable energy generation.

In terms of land-use, sustainable agriculture offers interesting potential for scaling up by increasing carbon stocks without substantially changing land use or competing for land, as demonstrated by case studies in Switzerland, Indonesia, Kenya, and Burkina Faso. Sustainable agriculture encompasses a wide range of practices, such as mulching, reduced tillage or specific local practices. Due to the variety of practices sustainable agriculture encompasses, the mitigation potential and carbon permanence of some techniques are not yet well understood. An added advantage of sustainable agriculture is that it is not significantly susceptible to further climate risks than conventional agriculture, as these techniques introduce some changes to the already used methods rather than replacing them by completely different practices. Moreover, it can provide added market value, although this depends on local public awareness or access to internationally recognized certifications, which are not always easily obtainable for smallholders. Additionally, increasing land competition in countries with significant forest covers could result in deforestation.

3.2 Alignment with national priorities

When assessing the potential of LMTs to scale up, it is important to carefully consider their mitigation potential as well as other co-benefits, as sometimes the latter can outweigh the former. This is particularly relevant for developing countries that have historically low contributions to climate change and where priorities align more with climate adaptation, poverty alleviation, and food security rather than with mitigation. In such scenarios, BECCS often does not play a major role, as it does not provide significant ecological co-benefits beyond mitigation. Moreover, in many developing countries, competition for biomass is high, as crop and forest residues constitute a large share of household energy sources or are fed to livestock.

For instance, Burkina Faso's LMT portfolio has been defined based on the NDC plan, which prioritizes actions that increase soil health and harvest security over mitigation. Locally adapted sustainable agriculture actions provide advantages over mainstream industrial agriculture by increasing water and nutrient retention, mitigating erosion (an increasingly important threat, particularly in the north of the country), and rising food security while contributing to increasing soil carbon without compromising land competition. This is also the case in Kenya or Nepal, where rice is key to food and income security, and dry seeded rice features both security and climate change mitigation advantages.

Aligned with the countries' NDC and/or national plans to increase the forest area by 2030, the scenarios of Kenya, Vietnam, Sweden, Nepal, and the Netherlands include forest actions within their portfolios. In addition, agrosilvopastoral techniques such as dehesas and montados are included in the Spanish and Portuguese scenarios. Both countries are prioritizing the further development of these traditional low-intensity (i.e., extensive) farming techniques as a way to make climate change mitigation and sustainable livestock production compatible.

On the other hand, for industrialized countries with high energy consumption and less domestic competition for biomass, BECCS is often the technique with the highest mitigation potential. For example, Sweden has identified BECCS as the key technique for achieving net-zero emissions by 2045. The combination of BECCS and Biochar is interesting, as biochar complements BECCS by bringing in the environmental co-benefits that BECCS lacks, although biochar often plays a complementary role in terms of mitigation, as identified in the Swedish scenario.

In specific contexts, biochar has been identified as a very advantageous option. For example, Vietnam is a country with a very intensive agriculture system that produces a lot of agricultural residues. Using them to produce biochar is a traditional technique that allows improving the soil's quality. However, it must be considered that these circumstances only apply in cases where the competition for biomass is low, such as Vietnam, but this could change if BECCS is implemented at a larger (regional or global) scale.

One of the main challenges of aligning the LMT portfolio to national priorities is to ensure that they are also sustainable. For instance, Portugal's eucalyptus trees sequester three times more carbon than local species while needing less maintenance, but they degrade the land. A similar case applies to Vietnam and Nepal, where afforestation with rapidly growing or high-timber-value tree species is often prioritized because of higher revenues in terms of carbon credits or wood, but they are detrimental in the long term as they constitute monocultures that decrease diversity and provide few(er) ecosystem services.

When co-benefits are the priority and funding is scarce, land regeneration (e.g., accelerating vegetation growth in an existing forest) yields better results both for adaptation and mitigation than implementing techniques that imply land-use change, while also being less exposed to climate-change related disturbances. This is exemplified by the narratives of Burkina Faso and Kenya.

Fire management can provide significant co-benefits for soil fertility and biodiversity, especially in ecosystems that are adapted to naturally occurring fires. Controlled fires can temporarily reduce carbon stocks, but they can also prevent larger and more destructive fires. These co-benefits have been considered in the Venezuelan scenario.

3.3 Future perspectives

Global warming is expected to have a widespread impact on various systems and to alter the application and effectiveness of low emission mitigation techniques (LMTs). Developing countries, which are heavily reliant on primary sectors, are likely to experience more pronounced effects compared to industrialized nations. As a result, implementing LMTs that enhance climate resilience is particularly important for developing countries. While some effects of global warming may lead to increased carbon stocks, such as the rise of the tree line to higher altitudes in alpine areas, such as expressed by the Swiss scenario, or the expansion of forest areas in boreal regions, it is generally detrimental to climate change mitigation.

The rise in pests is an ongoing trend that is expected to intensify in the coming years, as noted by the Spanish and Dutch narratives. To ensure the success of LMTs, it is essential to design and implement strategies that avoid monocultures and incorporate suitable plant species to minimize the exposure to parasites. Climate change is also expected to increase the risk of forest fires, and current fire suppression policies may need to be re-evaluated to incorporate controlled fires that prevent destructive mega fires.

Climate change is expected to largely increase forest fire-prone conditions. Most governments apply a zero-fire policy, meaning that every forest fire should be avoided, and forest fire management actions are almost exclusively directed to forest fire suppression. With a higher incidence of megafires, fire management policies will need to change to allow for small scale, controlled forest – where possible in combination with using livestock grazing to manage undergrowth - fires that mitigate the risk for more destructive big fires.

Finally, as detailed in Deliverable 4.1: Climate Risk Assessment and Initial Risk Management Plan (Picon & Spijker, 2022), climate change is (bringing and) expected to bring more climate extreme event, potentially creating disturbances in the techniques, and affecting their effectiveness, as mentioned in all scenarios. LMTs posses' variable degrees of exposure to climate disturbances, with engineered solutions being often regarded as the least vulnerable. However, disturbances in temperatures and rain patters could heavily affect afforestation efforts, especially in the early phases, growth patterns of grasses and legumes, or yields of more sensitive crops such as coffee. This could compromise carbon stocks provided by the techniques and the general success of the techniques.

3.4 Institutional, social and policy contexts

Some of the challenges the implementation of LMTs face is the lack of information and data regarding carbon stocks and soil composition. This makes it difficult to assess the effectiveness of the implemented action or to set a baseline that would allow for the participation in carbon markets. This is particularly relevant for developing countries, where capacity to perform widespread soil studies is scarce, especially in vast and sparsely populated areas, as was expressed by the scenarios of Kenya and Burkina Faso.

Political stability and security also play a role in the successfully implementing these techniques, as policy frameworks and funding schemes must remain stable for land users to trust and use them. Low political stability disincentivizes investments and actions that bring benefits in the long term and prioritizes short-term results and the continuation of known practices, a consequence of the so-called 'poverty trap'. This was explicitly expressed by the scenario of Burkina Faso.

LMTs also face bureaucratic challenges regarding their definition, as expressed by the Dutch, Spanish and Portuguese narratives. A necessary condition to create policies around a technique is to be able to define it, but certain LMTs, such as agroforestry, are difficult to define (how many trees per hectare and with which distribution constitute an agroforestry system? Do agricultural or livestock farming incentives apply to dehesas and montados?). Policymakers will need to address these topics to allow for the creation of supportive regulatory frameworks.

Demographic changes are also expected to challenge the implementation of LMTs; a worldwide trend towards rural emigration to urban areas will translate into a decreased availability of labour (i.e., depopulation) in rural areas and an increase in labour costs. This has two implications; the first is that LMTs that decrease costs and labour requirements will have a greater upscaling potential, such as dry seeded rice in Nepal. Second, LMTs that foster the active involvement of local communities will help slowing down or reversing this trend, such as Dehesas and Montados in Spain and Portugal or forest management in Nepal. Linked to this fact is the potential decrease in regulatory support for activities in rural areas as higher rates of the population concentrate in urban areas, further removing the attention and priorities from the countryside and hindering the development of these techniques.

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