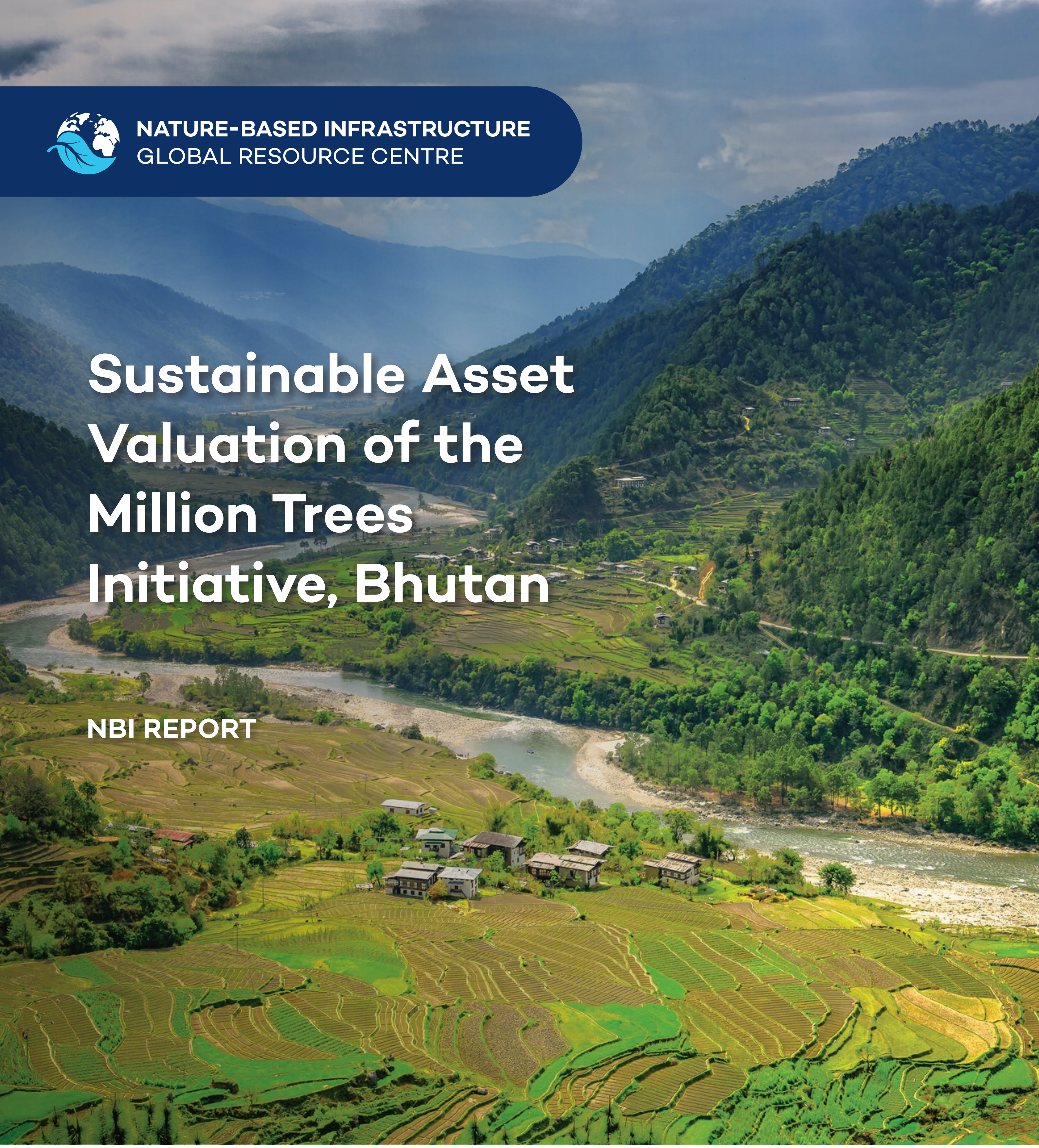

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Sustainable Asset Valuation of the Million Trees Initiative, Bhutan

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September 2022

Published by the International Institute for Sustainable Development

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Sustainable Asset Valuation of the Million Trees Initiative, Bhutan

September 2022

Written by Emma Cutler and Marco Guzzetti

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Acknowledgements

We would like to thank Pem Lama, Joshua Goldberg, Sonam Phuntsho, Sonam Wangmo, and Ugyen Dorji from the Bhutan Ecological Society for their contributions and engagement throughout this assessment. Many thanks also to Matthew Gouett for his assistance with the financial analysis and to Andrea M. Bassi, Liesbeth Casier, and David Uzsoki for their guidance and feedback on this report.

Author contributions: Authors are listed in alphabetical order. Emma Cutler conceptualized and developed the system dynamics and agent-based models, prepared the cost-benefit and financial analyses, and led the writing of this report. Marco Guzzetti conducted the spatial analysis and wrote the corresponding appendix.

Executive Summary

Human–wildlife conflict, water scarcity, flooding, and landslides all threaten agricultural livelihoods in Bhutan. As a result, almost 30% of the country's arable land is fallow. The challenges surrounding agricultural production, combined with education and job opportunities and the availability of public services, have motivated rural–urban migration. This has led to labour shortages, which further contribute to the low rates of land utilization. Extensive fallow areas not only impact rural income but also make communities more vulnerable to flooding and landslides and decrease agricultural production.

Through the Million Trees Initiative, the Bhutan Ecological Society (BES) aims to plant 1,000,000 high-value plantation trees to regenerate fallow land. The objective is for these trees to support rural livelihoods and landscapes by

- Providing income from fruit, timber, and fodder
- Creating jobs in nurseries
- Reducing landslides and erosion
- Mitigating flooding
- Sequestering carbon.

The project aims to plant trees on 809 hectares of fallow land and restore 1,214 hectares of degraded forest with the possibility of scaling up in the future. It will support over 5,000 smallholder farmers, assumed to be 2,500 men and 2,500 women. This project is in line with Bhutan's multiple forestry policies related to sustainable management of forests and watersheds and reforestation of degraded lands.

This report presents the results of a Sustainable Asset Valuation of the Million Trees Initiative. Stakeholders can use this assessment to secure funding, generate local buy-in, and scale up tree planting initiatives (Table ES4). The assessment relies upon outputs from a spatially explicit analysis, a system dynamics model, and an agent-based model to quantify the social and environmental externalities of tree planting in rural Bhutan. These impacts are compiled into an integrated cost-benefit analysis, and we calculate the internal rate of return (IRR) and net present value (NPV) of the project over a 20-year time horizon.

In collaboration with BES, the following policy scenarios were identified:

- Fifteen hectares of fruit and timber plantations are established (results are reported for both subtropical and temperate regions).
- Electric fences are constructed to reduce human–wildlife conflict. This scenario allows us to compare trees to a grey infrastructure alternative that could also be used to boost rural income.
- Fifteen hectares of fruit and timber plantations are established, and electric fences are constructed.
- Fifteen hectares of trees are planted to restore habitat.

For the integrated cost-benefit analysis, we also consider several environmental and economic conditions. These include scenarios in which we assume the study area is exposed to floods and landslides, the local community can benefit from carbon credits, non-wood forest products (NWFPs) are economically important, seedlings are sourced from local nurseries, and the potential income that could be earned in urban areas increases with time. For the financial indicators, we focus only on the scenarios that do not include these additional aspects.

Results Summary

The key messages that emerge from our analysis are as follows:

- Plantations can boost rural income, reduce the area of fallow land, and slow rural population decline. These outcomes lead to net benefits of more than USD 270,000 over 20 years and a benefit-to-cost ratio greater than 18 (Table ES1).
    - Fruit plantation production is important for reducing rural–urban migration because potential carbon credits are small compared to the value of plantation products. Specifically, fruit production creates USD 265,500–USD 413,400 over 20 years, compared to USD 3,400 from carbon credits. Furthermore, without plantation products, habitat creation alone does not boost income and so has a minimal impact on population (Tables ES1 and ES2).
    - Plantations may increase human–wildlife conflict. This results in losses of USD 8,300–USD 9,100. However, the value of plantation products is over USD 250,000. Thus, this increase more than offsets the losses (Table ES1).
- Fences can reduce human–wildlife conflict but do not generate income (Table ES1). Thus, although this grey infrastructure reduces losses from wildlife, it does not generate additional income.
- Benefits of tree planting may be greater in locations that are vulnerable and exposed to flooding or landslides. For example, avoiding one landslide increases the benefit-to-cost ratio of plantations from 18.6 to 19.1 in subtropical areas and from 30.5 to 31.1 in temperate regions. Similarly, reducing flood damage by 30% results in benefit-to-cost ratios of 19.0 and 31.0 in subtropical and temperate regions, respectively (Table ES1). This demonstrates that plantations are a cost-effective way to increase climate resilience in Bhutan.
- NWFPs increase household income by USD 8,027 over 20 years, but gathering NWFPs worsens human–wildlife conflict, leading to losses of over USD 30,000. Thus, the cumulative net benefits, compared to a scenario in which people do not gather NWFPs, are negative (Table ES2).
- Nurseries reduce the costs of planting trees and create jobs. This raises the net benefits by approximately USD 200,000 (Table ES2).

- Tree planting may be less effective at slowing migration in places where pressure to leave rural areas is very strong. For example, the benefit-to-cost ratio is smaller when urban income increases than when urban income is constant (Table ES2).
- Plantations are, financially, a better way to support rural livelihoods than electric fences or tree planting for habitat restoration alone. Specifically, subtropical plantations have an NPV of USD 196,000, and temperate plantations have an NPV of USD 305,000. Furthermore, the IRR of plantations is over 35% (Table ES3).

In summary, plantations create income for farmers and mitigate flooding and landslides, sequester carbon, and improve habitat quality. In quantifying these impacts, we find that plantations are financially superior to electric fences, which reduce human–wildlife conflict but have only a small impact on household income. Comparing plantations to tree planting for habitat restoration alone, only plantations generate direct economic benefits for farmers. From this perspective, therefore, plantations are preferable to habitat restoration.

Restoring degraded and fallow land can also reduce flooding and landslides. In this way, tree planting would reduce the exposure of people and government-managed timber plantations to extreme precipitation. The climate adaptation benefits combined with the direct economic impacts of plantations make tree planting a valuable undertaking in Bhutan. These results make a financial case for such projects.

Table ES1. Undiscounted integrated cost-benefit analysis over 2022–2041 relative to a scenario with no intervention. Over the 20-year time horizon, plantations increase household income by over USD 18 per dollar invested, whereas fences have a benefit-to-cost ratio of only 1.4. While habitat restoration has benefits beyond reducing human–wildlife conflict, these could not be quantified because of lack of accurate data. The net benefits of habitat restoration are therefore likely underestimated. When plantations reduce landslide and flooding impacts, net benefits and the benefit-to-cost ratio are higher.

	Subtropical plantations	Temperate plantations	Fences	Fences with subtropical plantations	Fences with temperate plantations	Habitat restoration	Flooding with subtropical plantations	Flooding with temperate plantations	Landslides with subtropical plantations	Landslides with temperate plantations
Direct costs (thousands USD)	15.5	14.7	8.7	24.2	23.4	31.2	15.5	14.7	15.5	14.7
Capital costs	*6.8*	*9.2*	*3.0*	*9.8*	*12.2*	*9.6*	*6.8*	*9.2*	*6.8*	*9.2*
Maintenance costs	*8.7*	*5.5*	*5.7*	*14.4*	*11.2*	*21.5*	*8.7*	*5.5*	*8.7*	*5.5*
Total benefits (thousands USD)	**288.2**	**448.1**	**12.4**	**300.5**	**460.5**	**0.4**	**295.3**	**454.5**	**296.5**	**456.4**
Net income from agriculture	*30.4*	*41.6*	*1.9*	*32.3*	*43.5*	*0*	*37.5*	*47.9*	*38.8*	*50.0*
Wages from building fences	*0*	*0*	*0.9*	*0.9*	*0.9*	*0*	*0*	*0*	*0*	*0*
Wages from jobs created in nurseries	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Net income from fruit plantations	*265.5*	*413.4*	*0*	*265.5*	*413.4*	*0*	*265.5*	*413.4*	*265.5*	*413.4*

	Subtropical plantations	Temperate plantations	Fences	Fences with subtropical plantations	Fences with temperate plantations	Habitat restoration	Flooding with subtropical plantations	Flooding with temperate plantations	Landslides with subtropical plantations	Landslides with temperate plantations
Income from timber plantations	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Income from carbon credits	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Income from NWFPs	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Human–wildlife conflict impact on income	*-7.7*	*-7.0*	*8.7*	*0.9*	*1.7*	*0.4*	*-7.7*	*-6.9*	*-7.7*	*-7.0*
Net benefits (thousands USD)	**272.7**	**433.4**	**3.7**	**276.4**	**437.1**	**-30.7**	**279.8**	**439.8**	**281.1**	**441.8**
Benefit-to-cost ratio	**18.6**	**30.5**	**1.4**	**12.4**	**19.7**	**0.0**	**19.0**	**31.0**	**19.1**	**31.1**

Table ES2. Undiscounted integrated cost-benefit analysis over 2022–2041 relative to a scenario with no intervention. Plantations with urban income increase values are relative to the urban income increase scenario with no action. Including nurseries and carbon credits increases the value of plantations, but the net benefits and benefit-to-cost ratio are lower when urban income increases.

	Subtropical plantations with nurseries	Temperate plantations with nurseries	Subtropical plantations with carbon credits	Temperate plantations with carbon credits	NWFPs	Habitat restoration with NWFPs	Habitat restoration with wildlife damage	Urban income increases with subtropical plantations	Urban income increases with temperate plantations
Direct costs (thousands USD)	21.2	17.2	15.5	14.7	0	31.2	24.7	15.5	14.7
Capital costs	*4.2*	*5.1*	*6.8*	*9.2*	*0*	*9.6*	*9.6*	*6.8*	*9.2*
Maintenance costs	*17.0*	*12.1*	*8.7*	*5.5*	*0*	*21.5*	*15.1*	*8.7*	*5.5*
Total benefits (thousands USD)	**497.2**	**657.1**	**292.4**	**452.1**	**-30.4**	**-9.1**	**0.3**	**284.5**	**442.9**
Net income from agriculture	*59.0*	*70.2*	*31.1*	*42.2*	*-4.9*	*-1.9*	*0*	*26.4*	*36.0*
Wages from building fences	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Wages from jobs created in nurseries	*181.8*	*181.8*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Net income from fruit plantations	*265.5*	*413.4*	*265.5*	*413.4*	*0*	*0*	*0*	*265.5*	*413.4*
Income from timber plantations	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Income from carbon credits	*0*	*0*	*3.6*	*3.4*	*0*	*0*	*0*	*0*	*0*
Income from NWFPs	*0*	*0*	*0*	*0*	*8.0*	*7.4*	*0*	*0*	*0*
Human–wildlife conflict impact on income	*-9.1*	*-8.3*	*-7.7*	*-7.0*	*-33.5*	*-14.6*	*0.2*	*-7.4*	*-6.6*
Net benefits (thousands USD)	**476.0**	**639.9**	**276.9**	**437.4**	**-30.4**	**-40.3**	**-24.5**	**269.0**	**428.2**
Benefit-to-cost ratio	**23.5**	**38.2**	**18.9**	**30.8**	**-**	**-0.3**	**0.0**	**18.3**	**30.2**

Table ES3. Financial analysis results

	Subtropical plantations	Temperate plantations	Fences	Fences with subtropical plantations	Fences with temperate plantations
NPV without opportunity cost (USD)	196,039	304,900	2,548	198,576	307,439
NPV with opportunity cost (USD)	186,452	291,918	-1,701	184,740	290,209
IRR without opportunity cost	45.8%	43.5%	25.2%	44.9%	42.9%
IRR with opportunity cost	37.3%	35.6%	2.0%	34.3%	33.6%

* N/A indicates that these IRR values are negative and cannot be calculated by Excel.

Table ES4. How stakeholders and decision-makers can use the results of this assessment

Stakeholder	Role in the project	Example of stakeholders	How can the stakeholder use the results of the assessment?
Implementer/ local civil society organizations	Responsible for designing and implementing the Million Trees Initiative.	BES	Lead implementing organizations can use the results of this assessment to secure additional funding for the Million Trees Initiative and to inform decisions regarding the remainder of the project and future restoration activities. They can also use the results of the assessment to generate local buy-in for tree planting.
Donors and investors	Provide funding for tree planting and nursery creation.	The Bhutan Foundation	Donors and investors can use the results of this assessment to inform funding decisions regarding tree planting and land restoration in Bhutan.
Local government	Generate local buy-in for tree planting and coordinate on-the-ground activities.	Dzongkhang and Gewog offices	Local governments can use this assessment to better understand and communicate the local benefits of plantations. This could help create interest in plantations among rural farmers, which is critical for the success of the Million Trees Initiative and other similar projects.

Stakeholder	Role in the project	Example of stakeholders	How can the stakeholder use the results of the assessment?
National government	Partner and support the plantations.	Ministry of Agriculture and Forests	National government agencies can use this assessment to justify scaling up tree planting initiatives throughout Bhutan.
Businesses and enterprises	Develop business around the idea to ensure the sustainability of the initiative.	Green Bhutan Corporation Limited, private businesses	The private sector and state-owned enterprises can use the results of this assessment to inform decisions and generate support for future afforestation and land restoration projects.

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Glossary

Discounting: A finance process to determine the present value of a future cash value.

Indicator: Parameters of interest to one or several stakeholders that provide information about the development of key variables in the system over time and trends that unfold under specific conditions (United Nations Environment Program [UNEP], 2014).

Internal Rate of Return (IRR): An indicator of the profitability prospects of a potential investment. The IRR is the discount rate that makes the net present value of all cash flows from a particular project equal to zero. Cash flows net of financing give us the equity IRR.

Integrated Valuation of Ecosystem Services and Tradeoffs: "A suite of models used to map and value the goods and services from nature that sustain and fulfill human life. It helps explore how changes in ecosystems can lead to changes in the flows of many different benefits to people" (Natural Capital Project, 2019, n.p.).

Methodology: The theoretical approach(es) used for the development of different types of analysis tools and simulation models. This body of knowledge describes both the underlying assumptions used as well as qualitative and quantitative instruments for data collection and parameter estimation (UNEP, 2014).

Model transparency: The degree to which model structure and equations are accessible and make it possible to directly relate model behaviour (i.e., numerical results) to specific structural components of the model (UNEP, 2014).

Model validation: The process of assessing the degree to which model behaviour (i.e., numerical results) is consistent with behaviour observed in reality (i.e., national statistics, established databases) and the evaluation of whether the developed model structure (i.e., equations) is acceptable for capturing the mechanisms underlying the system under study (UNEP, 2014).

Net benefits: The cumulative amount of monetary benefits accrued across all sectors and actors over the lifetime of investments compared to the baseline, reported by the intervention scenario.

Net Present Value: The difference between the present value of cash inflows net of financing costs and the present value of cash outflows. It is used to analyze the profitability of a projected investment or project.

Scenarios: Expectations about possible future events used to analyze potential responses to these new and upcoming developments. Consequently, scenario analysis is a speculative exercise in which several future development alternatives are identified, explained, and analyzed for discussion on what may cause them and the consequences these future paths may have on our system (e.g., a country or a business).

Simulation model: Models can be regarded as systemic maps in that they are simplifications of reality that help to reduce complexity and describe, at their core, how the system works. Simulation models are quantitative by nature and can be built using one or several methodologies (UNEP, 2014).

1.0 Introduction

Human–wildlife conflict, water scarcity, flooding, and landslides all threaten agricultural livelihoods in rural Bhutan. The challenges surrounding agricultural production, combined with education and job opportunities and the availability of public services, motivate rural–urban migration. This has led to labour shortages, which have become one of the most common constraints faced by rural households. As a result, land is under-utilized, with approximately 30% of the country's arable land left fallow (National Statistics Bureau of Bhutan, 2018b; Renewable Natural Resources Statistics Division Directorate Services, 2019).

Bhutan has many policies in place to ensure sustainable management of forests and watersheds and to promote reforestation of degraded lands. For example, there is a mandate, included in the constitution, to maintain at least 60% of the country under forest cover (Suberi et al., 2016; Wangdi et al., 2013). Thus, planting trees on fallow and degraded lands represents a natural means of supporting rural agricultural livelihoods in Bhutan.

Through the Million Trees Initiative, the Bhutan Ecological Society aims to plant 1,000,000 high-value plantation trees to regenerate fallow land and restore degraded forest. The objective is for these trees to support rural livelihoods and landscapes by

- Providing income from fruit, timber, and fodder
- Creating jobs in nurseries
- Sequestering carbon[1]
- Reducing landslides and erosion
- Mitigating flooding.

By the end of the planned 5-year project, the Million Trees Initiative will have planted trees on 809 hectares of fallow land and restored 1,214 hectares of degraded forest. The project will support over 5,000 smallholder farmers, including at least 2,500 men and 2,500 women (Bhutan Ecological Society, n.d.). It is also possible that the project could be scaled up to restore more land.

To implement the Million Trees Initiative, the Bhutan Ecological Society has formed formal partnerships with the Department of Agriculture of the Ministry of Agriculture and Forests, Green Bhutan Corporation Limited, and Natural Resources Development Corporation. Throughout the initiative, they will collaborate with local communities to plant trees and will provide capacity-building programs for farmers focused on plantation and nursery management (Bhutan Ecological Society, n.d.).

[1] There is currently no mechanism in place to compensate farmers for carbon credits. We include payments for carbon credits as a hypothetical scenario and present results both with and without this benefit.

The Bhutan Ecological Society officially launched the Million Trees Initiative in April 2021. To understand the potential impact of the project, the Society has engaged in a formal valuation of the potential costs and benefits of planting high-value trees.

In addition to direct economic benefit to farmers, the project can have multiple social and environmental benefits and reduce the need to invest in built infrastructure. To quantify these multiple co-benefits, we have applied the Sustainable Asset Valuation (SAVi) methodology to the Million Trees Initiative. The assessment uses outputs from a spatially explicit analysis, a system dynamics (SD) model, and an agent-based model (ABM) to quantify the social and environmental externalities of tree planting in rural Bhutan. These impacts are compiled into an integrated cost-benefit analysis, and we assess the financial performance of the project over a 20-year time horizon. In this report, we present the results of the SAVi assessment and discuss the economic impacts of plantations compared to grey infrastructure.

2.0 Methodology

The starting point for the SAVi assessment is a system map, called a causal loop diagram, that displays important aspects of the social–environmental system and relations among variables. This diagram is co-created, informed by data and literature, and helps us to define the scope of analysis. Based on what emerges from the causal loop diagram, we use a spatially explicit analysis to quantify the ecosystem services of tree planting. These ecosystem services, as well as other costs and benefits, are quantified using system dynamics and agent-based models, which are informed by the causal loop diagram. The outputs of these simulation models are compiled in an integrated cost-benefit analysis that includes social and environmental externalities, in addition to monetary indicators typically included in economic valuations. Finally, we use the results of the cost-benefit analysis to assess the financial performance of the project over 20 years.

2.1 Causal Loop Diagram

A causal loop diagram shows relations among components of a system. Arrows indicate causality, and plus and minus signs are used to show the direction of causality. A plus sign means that two variables change in the same direction (if the first increases, the second also increases, and if the first decreases, so does the second), while a negative sign means that they change in opposite directions (if one increases, the other decreases and vice versa). Feedback loops are labelled as either reinforcing (R) or balancing (B). Reinforcing loops amplify change, so that an increase or decrease in a variable results in further change in the same direction. Balancing loops, on the other hand, dampen change.

We developed two causal loop diagrams to show how tree planting can affect household income and population dynamics at the village level. The first (Figure 1) is simpler than the second and includes only the most important relations and feedbacks. These are the interactions that, when included in an SD model, highlight the big-picture impacts of tree planting and other interventions.

The second diagram (Figure A1) is a more complete representation of the system. The relations in this diagram provide context for the Million Trees Initiative but do not necessarily need to be included in a mathematical model to understand how trees affect other components of the system.

Both diagrams were developed collaboratively with staff from the Bhutan Ecological Society. They were created to explain population and land cover changes observed in many parts of the country. However, due to social, economic, and environmental diversity, not all relations and feedbacks in the diagrams are relevant for all villages. The local context is critical for understanding the dynamics.

2.1.1 Population and Land Dynamics in Rural Bhutan

Historically, population growth in rural Bhutan has created a need for agricultural and settlement land. As forest habitat has been converted into villages and agricultural land, wild animals and humans have had increased contact. This contact often produces human–wildlife conflict following animal damage to crops or livestock, which reduces agricultural productivity.

Flooding and landslides create additional challenges for farmers. Extreme precipitation, combined with deforestation, which limits water retention, leads to these natural disasters that cause tremendous damage. These challenges are compounded by a lack of infrastructure and public services in rural areas. Extreme precipitation is projected to become more intense with climate change, which will further increase the risk of flooding and landslides (World Bank Group & Asian Development Bank, 2021)

While these rural hardships have emerged, there has also been an increase in urban job opportunities. More widespread formal education has made these urban prospects more accessible. As a result, there is declining interest in agriculture, particularly among young people. This has spurred rural–urban migration.

As people leave rural locations, large areas of land are left fallow due to labour shortages. Consequently, those who do not leave face further challenges. The loss of productive land limits agricultural income. Wild animals that have developed a taste for crops come in closer to the village in search of food. Natural disasters continue. These threats to rural livelihoods motivate more migration to urban places, creating a vicious cycle of population decline and rural hardship (R1 and R2 in Figure 1 and Figure A1).

The causal loop diagrams (Figure 1 and Figure A1) show how relations and feedbacks among components of the social-environmental system have created these problems. However, not all processes apply in all villages.

For example, in places where wildlife prefer wild food to crops, population decline may create more space for wildlife, which can decrease human–wildlife contact (B1).

Furthermore, gathering non-wood forest products (NWFPs), such as wild fruits and vegetables, to increase household income depletes wild food sources. This practice has become popular in parts of Bhutan and may spur some wild animals to use areas in and around human settlements in search of alternate food sources, worsening conflict. This could increase outmigration. The subsequent decline in population would relieve pressure on wild food sources, resulting in less human–wildlife conflict. However, if these animals learn to prefer crops, then conflict worsens.

In response to these challenges, the Million Trees Initiative aims to plant trees across the country.

Trees produce goods, reduce flash flooding and landslides, and may result in carbon credits, all of which can create household income. As shown by R1, this increase in income can discourage outmigration and, therefore, slow or possibly reverse rural population loss. With a larger population, there will be more land under cultivation, which will further improve livelihoods.

At the same time, population growth is likely to lead to wild habitat loss. Species that prefer wild foods may be pushed farther away, leading to less contact with people, as demonstrated by R2. This would have a beneficial impact on income. Conversely, loss of habitat will force many animals closer to human settlements in search of food. This will worsen human–wildlife conflict, leading to lower agricultural productivity and, therefore, less income (B1). The impact on human–wildlife conflict in a specific village depends on the extent to which wildlife prefer crops over wild food sources, among other factors.

Instead of planting trees to directly benefit communities via plantations and natural disaster mitigation, trees can be strategically planted to create habitat for wildlife. If this habitat is created farther from a village, this could draw animals, particularly those that prefer wild foods, away from settled areas, reducing human–wildlife conflict. However, if this habitat is close to a village, it could attract wildlife nearer to agricultural fields and make human–wildlife conflict worse.

There are also a variety of threats to tree survival, such as pests and disease, lack of water availability, damage by wild animals, and limited village capacity to care for trees.

The negative impact of wildlife on trees could reduce or enhance the impact of tree planting. For example, if trees create habitat, they could attract wildlife, which may damage seedlings (B2).

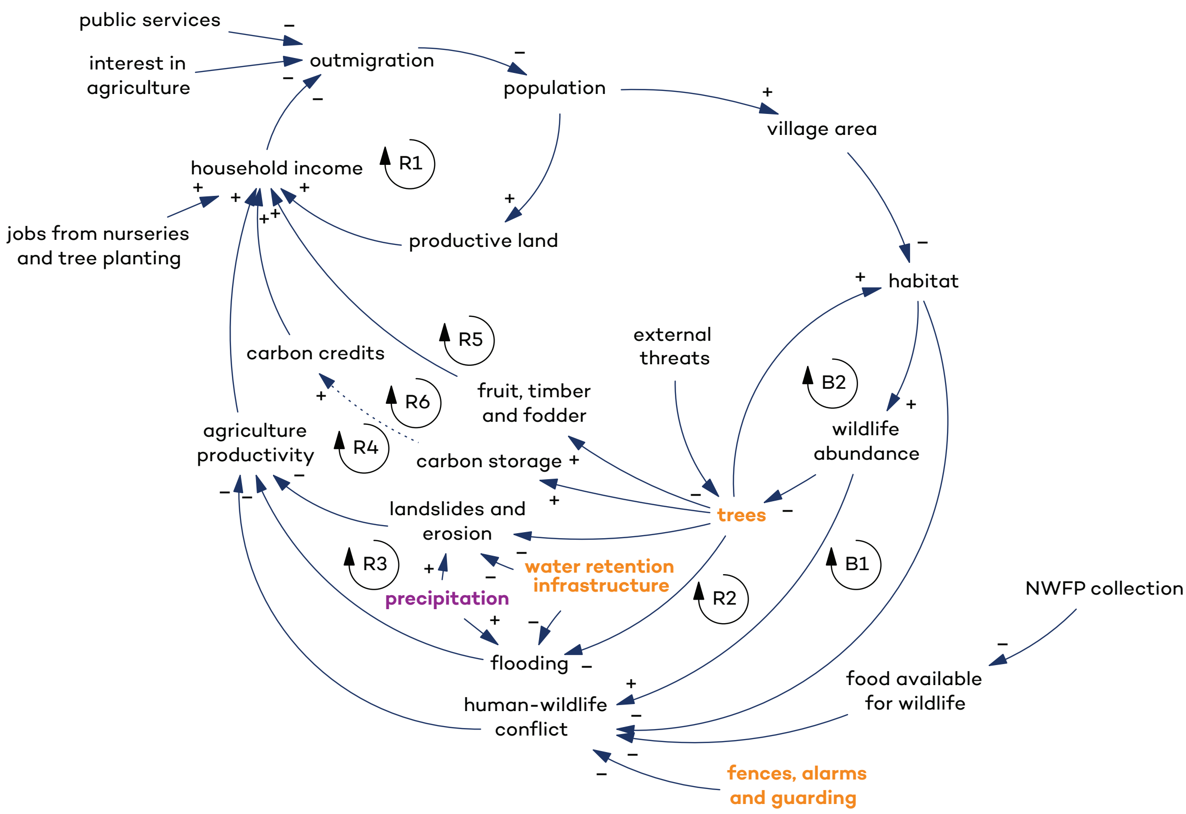
Conversely, trees mitigate flooding and landslides, which increases agricultural productivity and household income. This slows migration, leading to population growth, village expansion, and habitat destruction, which may shrink the wildlife population. Thus, the trees are better able to survive (R3 and R4).

Similarly, fruit, timber, and fodder (and possibly carbon credits) from trees create income, so there is less outmigration and a larger population, requiring more area. As the village encroaches on wildlife habitat, the abundance of wildlife decreases. By removing this threat, trees can produce more value (R5 and R6).

We also note that many forms of wildlife have a positive impact on trees in the form of pollination and fruit/seed dispersal. However, these synergistic interactions are more significant for older trees and have less impact on seedling survival, and so we do not include them in this analysis.

Instead of tree planting, built infrastructure, such as retaining walls, gabion walls, and drainage systems, could be used to mitigate flooding and landslides. Much like trees, this can stimulate agricultural production, leading to more income and population growth. Fences, alarms, and guarding can be used to mitigate crop damage and the resulting human–wildlife conflict. This would also increase agricultural productivity and income but would not provide the other high-value products and carbon credits that trees can create.

Figure 1. Causal loop diagram. Purple variables are climate inputs, and orange indicates possible policy interventions. Feedback loops help explain the observed patterns of declining rural livelihoods.



Source: Authors' diagram created using Vensim.

2.2 Spatially Explicit Analysis

From the causal loop diagram, landslides, flooding, habitat quality, and carbon storage are important factors to consider in the SAVi assessment. These are estimated using a spatially explicit approach. We use the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) suite of spatial models to quantify carbon storage, habitat quality, and runoff retention. The analysis uses land cover maps from 1992, 2000, 2010, and 2015 to calculate changes in these ecosystem services over time. We then compare the results to places with high landslide hazard and population density. This analysis provides background and context for the Million Trees Initiative and informs assumptions that were necessary for the SAVi assessment.

We calculate the same indicators for 2016 using a higher-resolution land cover map. At the national level, this provides a potentially more accurate estimate for these ecosystem services. We also calculate carbon storage, habitat quality, and runoff retention for a smaller area. We consider both current land cover and future land cover assuming some shrub land is converted to plantations. This provides a proof-of-concept, demonstrating how this analysis can be used to calculate ecosystem services provided by tree planting at the local level.

Detailed methods and assumptions for the spatial analysis are in Appendix C. The spatial analysis uses land cover data from the European Space Agency and the Bhutan Ministry of Agriculture and Forests.

2.3 Simulation Models

We developed two models that simulate comparable systems. The first is an SD model that takes a top-down approach, while the other is a bottom-up ABM. By changing parameter values that correspond to local conditions, the models can be customized for a specific village or to test scenarios within a single village. Both models are based on the dynamics described by the causal loop diagram. However, they serve different purposes. Detailed descriptions of and numerical inputs for the models are in Appendix B.

The simulation models rely on data from many sources, including

- The National Statistics Bureau of Bhutan
- The Renewable Natural Resources Statistics Division of the Bhutan Ministry of Agriculture and Forests
- The Food and Agriculture Organization of the United Nations
- The United Nations Development Programme
- International peer-reviewed literature
- Local knowledge.

2.3.1 SD Model

The SD model was built using Vensim DSS version 8.2.1. It forms the basis of the integrated cost-benefit analysis. We use the model to simulate population and land cover change both with and without tree planting. This allows us to calculate the costs and benefits of taking no action, planting trees, or building grey infrastructure to address human–wildlife conflict.

In the model, population changes in response to births, deaths, and migration. The birth rate decreases over time, while the death rate is roughly constant, with small annual variations (National Statistics Bureau of Bhutan, 2018a, 2019).

People earn income from agricultural production, NWFPs, fence construction, and tree planting and production. Migration depends on the ratio between per capita income earned in rural areas and the average per capita income that could be earned in urban areas. When this ratio is equal to 1, there is no migration. If the ratio is less than 1, there is migration to urban areas, and when the ratio is greater than 1, there is net migration into the rural area. In addition to the sources of income listed above, we also include an exogenous, constant "other income," which represents non-agricultural income and wages.

Land is classified as either agricultural land, fallow land, plantation area, secondary forest, or forest. When the population shrinks, agricultural land is left fallow. When the population grows, fallow land and/or forest is converted to productive cropland.

2.3.2 ABM

We use a spatial ABM to simulate how individual people and animals interact with the landscape using NetLogo modelling environment (Wilensky, 1999). Like the SD model, the ABM estimates land cover and population changes due to tree planting and external pressures.

The ABM consists of people and wildlife that exist within a confined area and interact with the landscape (Figure 2). People earn income from agricultural and plantation patches. Herbivores move through the landscape in search of food.

As with the SD model, there are five land cover classes: forest, agriculture, fallow, plantation, and secondary forest. Agricultural land is organized into landholdings, which are farmed by individual households. Households are comprised of people who earn income from agriculture, tree planting, fruit production, and building/maintaining fences.

The probability that a person migrates to an urban area depends on the ratio between that individual's income and the average income that could be earned in an urban location. If income is lower than what could be earned in an urban area, the individual may emigrate. If income is higher than what could be earned in an urban area, then a new person may migrate into the household.

Land productivity of a particular landholding depends on the ratio between household size and agricultural area. If a household is small relative to its land, productivity is low, and some land may be fallowed. If a household is large compared to its land, productivity is high, and some fallow land or forest may be converted to agriculture. When wildlife eat from agricultural or plantation land, the value produced by that land is decreased.

Figure 2. ABM visualization. Dark green areas are forest, black areas are fallow, light green areas are plantations, and other colours represent individual landholdings. Areas protected by fences are marked with a yellow X. Each person corresponds to a household, and the white animals are wildlife.

Source: Authors' diagram created using NetLogo (Wilensky, 1999).

Inputs for the ABM are estimated from the same sources as the SD model. In this way, the models are consistent with each other. The ABM also provides additional insights.

For example, when considering the impact of human–wildlife conflict on household income, it is necessary to simulate the number of contacts between people and animals under varying conditions. At the macro level, it is challenging to define equations that describe these dynamics. However, at the individual level, it is possible to make assumptions about wildlife preference for crops and fruit over wild food and the impact of fences on the accessibility of cultivated food. Thus, we can use the ABM to simulate individual-level behaviour and use the output to estimate the number of contacts. This helps us define and calibrate equations in the SD model.

Furthermore, the spatial relationships between people and wildlife are important for understanding human–wildlife conflict. The ABM allows us to explicitly include these spatial dynamics in a way that is not possible with the SD model.

Finally, the ABM creates an animation of people and animals moving in their changing environment. This visual representation of the system can serve as an effective communication tool with local stakeholders. This type of image can be more accessible than a graph or other numerical output and can therefore help generate local buy-in for tree planting.

2.4 Cost-Benefit Analysis

Costs and benefits are drawn from the causal loop diagram. Costs included in the model are

- Costs to purchase and plant trees
- Costs to establish and maintain nurseries
- Costs to build and maintain electric fences to reduce human–wildlife conflict.

Benefits are in the form of income. Sources of income are

- Agricultural production
- Jobs from building fences to prevent human–wildlife conflict
- Jobs created in nurseries
- Fruit and timber income from plantations
- Carbon credits
- NWFPs
- Timber revenue (a share of which is returned to the local community in the form of wages).

For benefits, we focus on household income because the Million Trees Initiative is designed to support rural livelihoods. Except for timber income, all benefits included in this model accrue to communities, whereas costs are borne by the Bhutan Ecological Society and funding agencies. In this way, the model simulates the effectiveness of investments in tree planting for boosting household income instead of the financial returns for investors. We also consider government revenue from timber plantations to assess the potential value of government involvement in tree planting. We assume that 50% of the government revenue will accrue to the local community in the form of wages for harvesting timber.

Direct costs are the sum of planting costs, timber plantation maintenance costs, and the cost of building and maintaining fences. Fruit plantation maintenance costs are deducted from household income, as it is assumed that fruit trees will be planted on private land, and landholders will be responsible for maintenance. Conversely, timber trees will be planted on public lands, and the Bhutan Ecological Society will cover maintenance costs.

To compare the household income created by planting trees with that of traditional, grey infrastructure, we consider electric fences to protect crops from wildlife damage. By constructing fences, we would expect that losses due to human–wildlife conflict will decrease, resulting in more household income. Furthermore, building fences creates jobs, an additional source of income.

2.5 Financial Analysis

Building on the results of the cost-benefit analysis, we use a financial analysis to consider how prices change over time, the time value of money, and the opportunity cost of the investment. We assume an inflation rate of 3.72% per annum, which is the average consumer price inflation for low- and middle-income countries over 2011–2020 (The World Bank, 2022). We do not use country-specific data because the World Bank does not have 10 years of inflation data for Bhutan. We use an annual discount rate of 6.5%. This is based on an approximate 3% yield of the 10-year U.S. treasury bonds (we use U.S. values because the project is funded using U.S. dollars) with a 3.5% risk premium added.

For this analysis, we consider the capital and maintenance costs of tree planting and fences and benefits in the form of household and government income over 20 years. We also felt that it was important to include revenue from harvesting timber, even though the timber harvest occurs more than 20 years after the start of the simulation. To do this, we first calculate the value of the harvest, accounting for inflation. We then discount this number back to present terms and include it in the financial analysis as a cash flow in the first year of the simulation.[2]

These calculations allow us to assess the financial viability of tree planting. We demonstrate the investment worthiness of tree planting by calculating the net present value (NPV) and internal rate of return (IRR). These financial indicators are useful for decision-makers interested in a holistic assessment of how tree planting affects household income.

[2] We include the value of the timber harvest in the first year of the simulation because we have discounted it to 2022 dollars. However, we acknowledge that this approach could affect the outputs of the financial indicator calculations.

We also include a scenario in which we consider the investment opportunity cost. With any investment, there is a cost associated with choosing one investment over all other investments. By including the investment opportunity cost, we compare the investment in tree planting against the increase in GDP that accrues to the economy when an average investment of the same size is made. This average investment is not sector-specific and may have social and environmental benefits and costs that are quite different from the tree planting initiative. To calculate the opportunity cost, we scale the investment amount by a fiscal multiplier of 1.6, the estimated multiplier for fiscal spending by governments in developing countries (Ilzetzki et al., 2013). This opportunity cost is spread over the first 5 years of the analysis. Despite the limitations of the method used, it is important to compare the different investment allocation options available. Practically, with this calculation, we assess whether tree planting generates more value compared to other public spending.

3.0 Scenarios

We parameterize the SD model for an "average" Bhutan village. That is, we use national averages for most data inputs. To test the impact of tree planting in different contexts and to account for data uncertainty, we run the models under a variety of scenarios with different input values. Policy scenarios simulated for this assessment are listed in Table 1. For the cost-benefit analysis and financial analysis, we use outputs from 2022 through 2041. However, we simulate the model for 2000 through 2060 to show the dynamics more comprehensively.

Table 1. Policy scenarios

Scenario	Assumptions
Baseline	The only sources of household income are agriculture and the exogenous "other income." Human–wildlife conflict leads to agricultural losses. There are no floods or landslides. People emigrate according to per capita income. No trees are planted.
Plantations*	Nine hectares (2,491 trees) of fruit plantations and 6 hectares (7,413 trees) of timber plantations are established in 2022. When fruit trees are mature, they produce fruit every year, which is a source of household income. Individual households must pay to maintain fruit trees. Timber trees produce value only when they are harvested. Timber trees are planted on public lands, and so timber revenue accrues to the government, with 50% being paid to the community as harvesting wages.
Habitat restoration	Fifteen hectares (18,533 trees) of trees are planted in 2022 to restore wildlife habitat. This increases the area of forest when trees mature.
Plantations* + nurseries	Nine hectares (2,491 trees) of fruit plantations and 6 hectares (7,413 trees) of timber plantations are established in 2022 using seedlings from nurseries. In addition to the impacts of plantations, nurseries create jobs and lower the cost of seedlings.
Plantations* + carbon credits	Nine hectares (2,491 trees) of fruit plantations and 6 hectares (7,413 trees) of timber plantations are established in 2022. Assumptions are the same as the plantations scenario with the addition of carbon credits as a source of household income.
Flooding	Every 5 years, there is a flood that reduces agricultural production by 10% in that year.
Flooding + plantations*	A flood occurs every 5 years. Nine hectares (2,491 trees) of fruit plantations and 6 hectares (7,413 trees) of timber plantations are established in 2022. This reduces the severity of floods, so production is decreased by only 7% when floods occur. Otherwise, assumptions are the same as the plantations scenario.
Landslides	Landslides occur in 2020 and 2030. In years when landslides occur, there is a 10% reduction in agricultural productivity. For the 4 years following a landslide, there is a smaller reduction in productivity.

Scenario	Assumptions
Landslides + plantations*	Nine hectares (2,491 trees) of fruit plantations and 6 hectares (7,413 trees) of timber plantations are established in 2022, which results in the same impacts as the plantations scenario. Additionally, a landslide occurs in 2020, but the 2030 landslide is avoided. Because we are unable to endogenously simulate the impact of trees on landslides, we instead calculate the benefits of potentially avoiding one landslide.
Fences	Same assumptions as the baseline scenario with the addition of 3 kilometres of fences constructed in 2022. This reduces the number of human–wildlife contacts and creates construction jobs.
Fences + plantations*	Fences are constructed and 9 hectares (2,491 trees) of fruit plantations and 6 hectares (7,413 trees) of timber plantations are established in 2022. This scenario combines the assumptions of the plantations and fences scenarios.
Habitat restoration + tree damage from wildlife	Fifteen hectares of trees (18,533 trees) are planted in 2022 to restore wildlife habitat. Trees are destroyed by wildlife at a rate that depends on density of wildlife in the forest. All impacts are the same as the habitat restoration scenario, but with fewer surviving trees.
NWFPs	Same assumptions as the baseline scenario, but people also gather NWFPs as a source of income. The intensity with which people collect NWFPs is assumed to double in 2010.
NWFPs + habitat restoration	People gather NWFPs with the intensity of collection increasing in 2010. Fifteen hectares of trees (18,533 trees) are planted as habitat restoration in 2022.
Urban income increase	Average per capita income that could be earned in urban areas increases linearly from USD 800 in 2000 to USD 1,000 in 2060. Otherwise, assumptions are the same as the baseline scenario.
Urban income increase + plantations*	Same assumptions as the plantations scenario with average per capita urban income increasing linearly from USD 800 in 2000 to USD 1,000 in 2060.

* All scenarios that include plantations are assessed twice—once for subtropical and once for temperate plantations.

With the ABM, we simulate the baseline, plantations, habitat restoration, fences, and fences + plantations scenarios. Differences include the following:

- For habitat restoration, the ABM requires that planted areas be adjacent to intact forest. Therefore, it is possible that fewer than 15 hectares are planted.
- All planted trees are assumed to survive.
- There is randomness built into the ABM. So, for each scenario, the model is run 100 times, and we use the average value at each time step as the model output. We also report the 10th and 90th percentiles.

In both models, it is possible to modify the specific policy parameters (e.g., the timing of interventions, the length of the fence, the number of trees planted, and the share of trees planted in fruit plantations, timber plantations, and forest). However, we present results only for the scenarios listed in Table 1, as this is sufficient to demonstrate the impacts of intervening in the system.

For the financial analysis, we consider the plantations, fences, plantations + fences, and habitat-restoration scenarios.

4.0 Results

From the simulation models, we find that

- Plantations can boost rural income, reduce the area of fallow land, and slow rural population decline. These outcomes lead to net benefits of more than USD 270,000 over 20 years and a benefit-to-cost ratio greater than 18 (Table 2).
    - Fruit plantation production is important for reducing rural–urban migration because potential carbon credits are small compared to the value of plantation products. Specifically, fruit production creates USD 265,500–413,400 over 20 years, compared to USD 3,400 from carbon credits. Furthermore, without plantation products, habitat creation alone does not boost income and so has a minimal impact on population (Table 2 and Table 3).
    - Plantations may increase human–wildlife conflict. This results in losses of USD 8,300–9,100. However, the value of plantation products is over USD 250,000. Thus, this increase more than offsets the losses. Fences can reduce human–wildlife conflict but do not generate income (Table 2).
- Benefits of tree planting may be greater in locations that are vulnerable and exposed to flooding or landslides. For example, avoiding one landslide increases the benefit-to-cost ratio of plantations from 18.6 to 19.1 in subtropical areas and from 30.5 to 31.1 in temperate regions. Similarly, mitigating flood damage results in benefit-to-cost ratios of 19.0 and 31.0 in subtropical and temperate regions, respectively (Table 2). This demonstrates that plantations are a cost-effective way to increase climate resilience in Bhutan.
- NWFPs increase household income by USD 8,027 over 20 years, but gathering NWFPs worsens human–wildlife conflict, leading to losses of over USD 30,000. Thus, the cumulative net benefits, compared to a scenario in which people do not gather NWFPs, are negative (Table 3).
- Nurseries reduce the costs of planting trees and create jobs. This raises the net benefits by approximately USD 200,000 (Table 3).
- Tree planting may be less effective at slowing migration in places where pressure to leave rural areas is very strong. For example, the benefit-to-cost ratio is smaller when urban income increases than when urban income is constant (Table 3).
- Plantations are, financially, a better way to support rural livelihoods than electric fences or tree planting for habitat restoration alone. Specifically, subtropical plantations have an NPV of USD 196,000, and temperate plantations have an NPV of USD 305,000. Furthermore, the IRR of plantations is over 35% (Table 6).

4.1 Plantations Boost Rural Income, Reduce Fallow Land, and Slow Population Decline

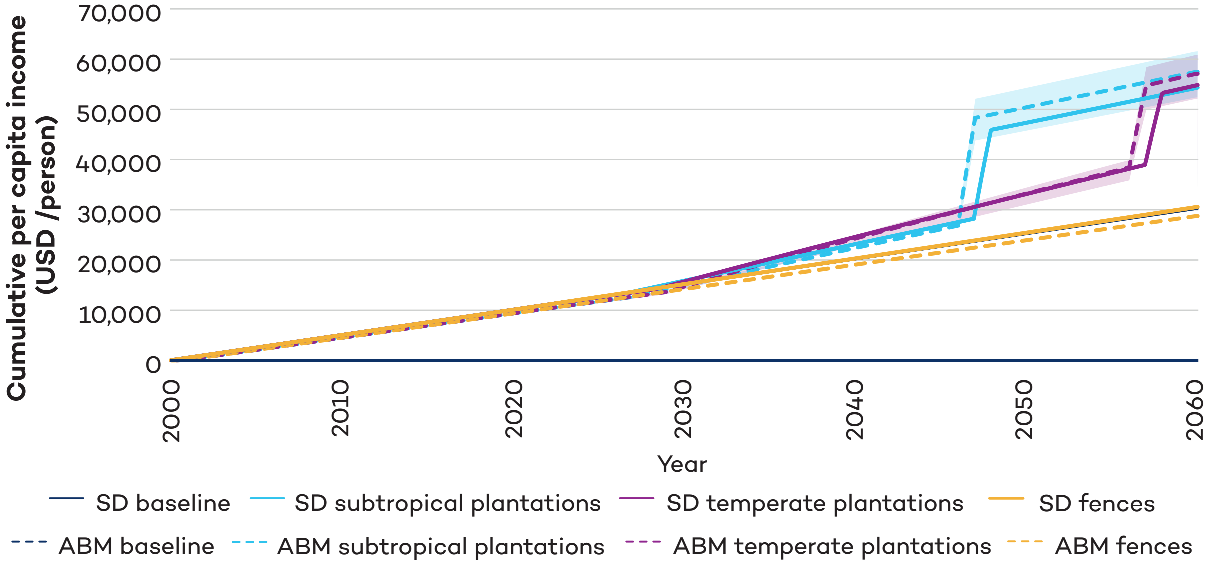
Planting trees leads to an increase in per capita income (Figure 3). This extra income slows and even reverses projected declines in rural populations (Figure 4). A sustained rural population greatly reduces the area of fallow land (Figure 5).

Because we do not simulate replanting after timber is harvested, there is a jump in fallow land at the time of harvest. However, the corresponding increase in population, which responds to income from timber, also leads to more agricultural land. This cultivation mitigates some of the increase in fallow area. This suggests that stimulating rural livelihoods with plantations can have positive impacts elsewhere in the system.

Plantations produce more value and have a higher benefit-to-cost ratio than building fences (Table 2). The SD model estimates that in the subtropical region, plantations create USD 269,000 more cumulative household income from 2022 to 2041 than fences.
In temperate regions, this number rises to almost USD 430,000.

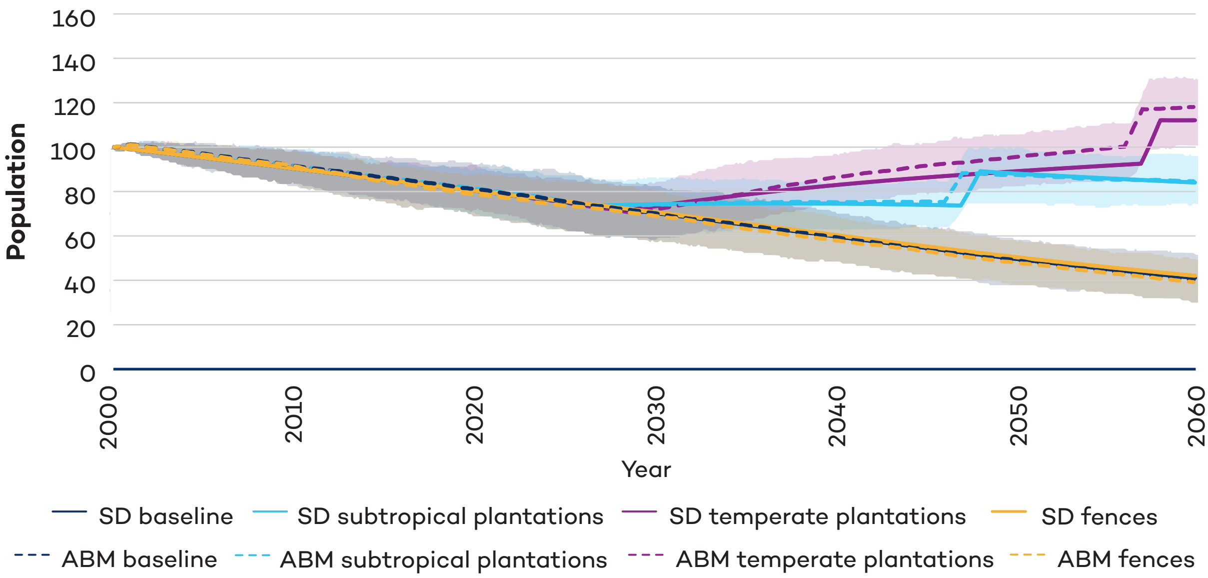
Plantations produce more value in temperate regions than in subtropical areas because we have assumed that the temperate plantations produce more fruit per tree and, on average, these fruits are more valuable. Furthermore, the temperate trees are cheaper to maintain. These differences more than offset the higher planting costs and longer maturity times in temperate regions.

Figure 3. Cumulative per capita income as estimated with the SD model and ABM for the baseline, plantations, and fences scenarios. Plantations can greatly increase per capita income, particularly at the time when timber is harvested. Fences have a very small impact on household income. Shading indicates the 10th and 90th percentiles of the ABM results. Figure extends beyond the 20-year time horizon that is most relevant for decision making to show the effect of harvesting timber.



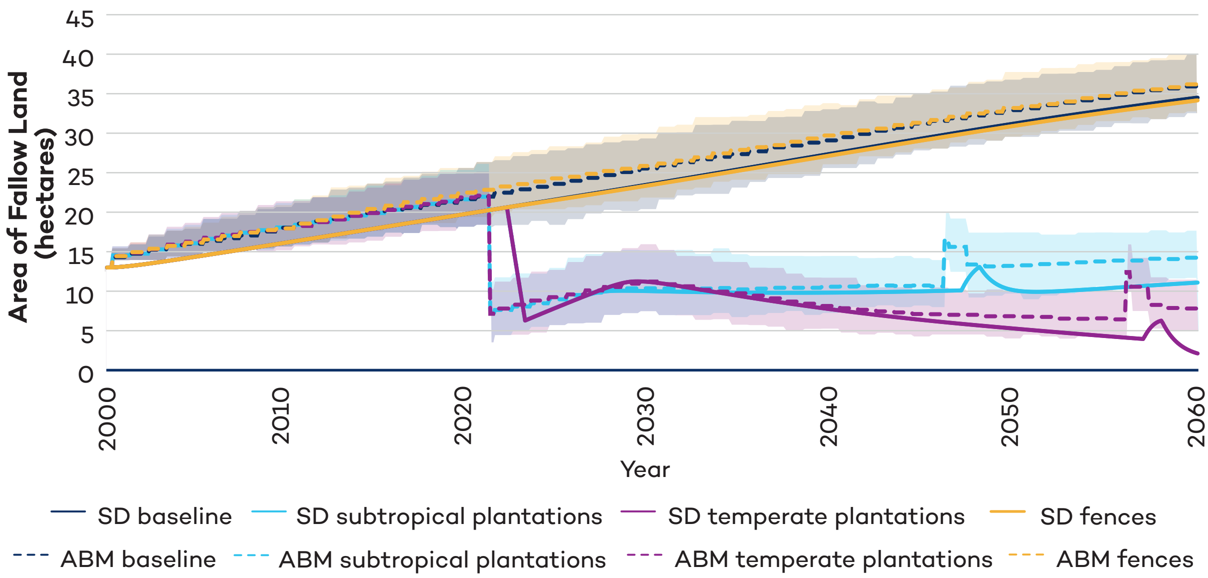
Source: Authors' diagram.

Figure 4. Population as estimated with the SD model and ABM for the baseline, plantations, and fences scenarios. In the baseline scenario, population decreases. Establishing plantations can slow, and in temperate regions may even reverse, this trend, while fences have a negligible impact. Shading indicates the 10th and 90th percentiles of the ABM results. Figure extends beyond the 20-year time horizon that is most relevant for decision making to show the effect of harvesting timber.



Source: Authors' diagram.

Figure 5. Area of fallow land as estimated with the SD model and ABM for the baseline, plantations, and fences scenarios. In the baseline scenario, the area of fallow land increases over time. Unlike fences, plantations decrease fallow area. Shading indicates the 10th and 90th percentiles of the ABM results. Figure extends beyond the 20-year time horizon that is most relevant for decision making to show the effect of harvesting timber.



Source: Authors' diagram.

Table 2. Undiscounted integrated cost-benefit analysis over 2022–2041 relative to a scenario with no intervention. The flooding with plantations values are relative to the flooding scenario with no action; landslides with plantations values are relative to landslides scenario with no action. Over the 20-year time horizon, plantations increase cumulative household income by over USD 18 per dollar invested, whereas fences have a benefit-to-cost ratio of only 1.4. While habitat restoration has benefits beyond reducing human–wildlife conflict, these could not be quantified because of lack of accurate data. The net benefits of habitat restoration are therefore likely underestimated. When plantations reduce landslide and flooding impacts, net benefits and the benefit-to-cost ratio are higher.

	Subtropical plantations	**Temperate plantations**	**Fences**	**Fences with subtropical plantations**	**Fences with temperate plantations**	**Habitat restoration**	**Flooding with subtropical plantations**	**Flooding with temperate plantations**	**Landslides with subtropical plantations**	**Landslides with temperate plantations**
Direct costs (thousands USD)	15.5	14.7	8.7	24.2	23.4	31.2	15.5	14.7	15.5	14.7
Capital costs	*6.8*	*9.2*	*3.0*	*9.8*	*12.2*	*9.6*	*6.8*	*9.2*	*6.8*	*9.2*
Maintenance costs	*8.7*	*5.5*	*5.7*	*14.4*	*11.2*	*21.5*	*8.7*	*5.5*	*8.7*	*5.5*
Total benefits (thousands USD)	**288.2**	**448.1**	**12.4**	**300.5**	**460.5**	**0.4**	**295.3**	**454.5**	**296.5**	**456.4**
Net income from agriculture	*30.4*	*41.6*	*1.9*	*32.3*	*43.5*	*0*	*37.5*	*47.9*	*38.8*	*50.0*
Wages from building fences	*0*	*0*	*0.9*	*0.9*	*0.9*	*0*	*0*	*0*	*0*	*0*
Wages from jobs created in nurseries	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Net income from fruit plantations	*265.5*	*413.4*	*0*	*265.5*	*413.4*	*0*	*265.5*	*413.4*	*265.5*	*413.4*

	Subtropical plantations	Temperate plantations	Fences	Fences with subtropical plantations	Fences with temperate plantations	Habitat restoration	Flooding with subtropical plantations	Flooding with temperate plantations	Landslides with subtropical plantations	Landslides with temperate plantations
Income from timber plantations	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Income from carbon credits	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Income from NWFPs	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Human–wildlife conflict impact on income	*-7.7*	*-7.0*	*8.7*	*0.9*	*1.7*	*0.4*	*-7.7*	*-6.9*	*-7.7*	*-7.0*
Net benefits (thousands USD)	**272.7**	**433.4**	**3.7**	**276.4**	**437.1**	**-30.7**	**279.8**	**439.8**	**281.1**	**441.8**
Benefit-to-cost ratio	**18.6**	**30.5**	**1.4**	**12.4**	**19.7**	**0.0**	**19.0**	**31.0**	**19.1**	**31.1**

Table 3. Undiscounted integrated cost-benefit analysis over 2022–2041 relative to a scenario with no intervention. Plantations with urban income increase values are relative to the urban income increase scenario with no action. Including nurseries and carbon credits increases the value of plantations, but the net benefits and benefit-to-cost ratio are lower when urban income increases.

	Subtropical plantations with nurseries	**Temperate plantations with nurseries**	**Subtropical plantations with carbon credits**	**Temperate plantations with carbon credits**	**NWFPs**	**Habitat restoration with NWFPs**	**Habitat restoration with wildlife damage**	**Urban income increases with subtropical plantations**	**Urban income increases with temperate plantations**
Direct costs (thousands USD)	21.2	17.2	15.5	14.7	0	31.2	24.7	15.5	14.7
Capital costs	*4.2*	*5.1*	*6.8*	*9.2*	*0*	*9.6*	*9.6*	*6.8*	*9.2*
Maintenance costs	*17.0*	*12.1*	*8.7*	*5.5*	*0*	*21.5*	*15.1*	*8.7*	*5.5*
Total benefits (thousands USD)	**497.2**	**657.1**	**292.4**	**452.1**	**-30.4**	**-9.1**	**0.3**	**284.5**	**442.9**
Net income from agriculture	*59.0*	*70.2*	*31.1*	*42.2*	*-4.9*	*-1.9*	*0*	*26.4*	*36.0*
Wages from building fences	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Wages from jobs created in nurseries	*181.8*	*181.8*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Net income from fruit plantations	*265.5*	*413.4*	*265.5*	*413.4*	*0*	*0*	*0*	*265.5*	*413.4*
Income from timber plantations	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
Income from carbon credits	*0*	*0*	*3.6*	*3.4*	*0*	*0*	*0*	*0*	*0*
Income from NWFPs	*0*	*0*	*0*	*0*	*8.0*	*7.4*	*0*	*0*	*0*
Human–wildlife conflict impact on income	*-9.1*	*-8.3*	*-7.7*	*-7.0*	*-33.5*	*-14.6*	*0.2*	*-7.4*	*-6.6*
Net benefits (thousands USD)	**476.0**	**639.9**	**276.9**	**437.4**	**-30.4**	**-40.3**	**-24.5**	**269.0**	**428.2**
Benefit-to-cost ratio	**23.5**	**38.2**	**18.9**	**30.8**	**-**	**-0.3**	**0.0**	**18.3**	**30.2**

4.2 Plantation Production Is Important for Reducing Rural–Urban Migration

Income from fruit production is important for reducing rural–urban migration in the short term. In the plantation scenarios, this is the largest benefit (Table 2). With this additional income, migration and the area of fallow land are reduced (Table 4).

Considering a 20-year time horizon, timber trees do not produce value because it takes 25 years for subtropical timber trees and 35 years for temperate timber trees to mature. However, when trees are harvested, we estimate that timber plantations could produce approximately USD 450 per tree. Thus, the value of plantations, and therefore the impact on population and fallow land, would be larger if we considered costs and benefits further into the future. However, this long time horizon is less relevant for decision making, so we consider only 20 years.

Planting trees that do not produce valuable goods does not increase income unless NWFPs are economically important or carbon credits are available. Using the high-resolution land cover map and village-level data on tree planting, it is possible to estimate the increase in carbon storage (see Appendix C for an example of how this is done using the InVEST models). Even without local data, we can estimate the order of magnitude of possible carbon credits. For example, we estimate that plantations could generate approximately USD 3,500 in carbon credits for the simulated village. This is much smaller than the value from fruit and would raise the benefit-to-cost ratio from 18.6 to only 18.9 in subtropical regions and from 30.5 to only 30.8 in temperate regions (Table 2 and Table 3). Thus, carbon credits would increase the value of tree planting, but plantations are an economical way to support rural livelihoods even in the absence of carbon credits.

If trees are planted only for habitat restoration with no plantation production, the area of fallow land decreases, but there is a negligible impact on income and population (Table 4). The spatial analysis shows that habitat quality increased over the years 1992–2015 (Appendix C).[3] This supports the conclusion that habitat restoration, although accruing some benefits, may not need to be prioritized to the same extent as income creation.

Furthermore, if wildlife damage some of the planted trees, net benefits will be lower. Habitat restoration can decrease the density of wildlife in villages and agricultural lands, which leads to less agricultural damage from wildlife. However, it takes many years for trees to mature, and so this benefit cannot be realized before animals damage the seedlings. Thus, habitat restoration alone has a small impact on rural communities in our models (Table 2 and Table 3). This result highlights the importance of plantation products in creating value for households. Nevertheless, when considering the impact on wildlife when people over-exploit NWFPs, habitat restoration can reduce the resulting increase in human–wildlife conflict (see Section 4.5).

[3] We note that the higher-resolution land cover map from 2016 revealed a lower habitat quality than the lower-resolution maps from 1992, 2000, 2010, and 2015. However, because of the different resolutions, the 2016 map may be picking up threats that do not appear on the coarser maps. Thus, the 2016 map is not comparable to the others.

Table 4. Population and area of fallow land in 2041 under all scenarios simulated using the SD model and ABM. For the ABM, we include the 10th and 90th percentiles in parentheses. All scenarios start with a population of 100 and 13 hectares of fallow land.

	Population in 2041		Fallow land in 2041 (hectare)	
Scenario	**SD**	**ABM**	**SD**	**ABM**
Baseline	59	58 (46–69)	27.9	29.5 (25.5–33.3)
Subtropical plantations	74	75 (63–84)	9.8	10.6 (7.8–14.3)
Temperate plantations	84	87 (75–99)	7.4	7.8 (4.5–11.5)
Subtropical plantations with nurseries	85	-	6.0	-
Temperate plantations with nurseries	94	-	3.5	-
Subtropical plantations with carbon credits	75	-	9.8	-
Temperate plantations with carbon credits	84	-	7.3	-
Fences	59	57 (46–67)	27.6	30.0 (26.0–33.5)
Fences with subtropical plantations	75	75 (63–86)	9.6	10.2 (7.3–13.5)
Fences with temperate plantations	84	88 (76–101)	7.1	7.9 (4.5–10.5)
Habitat restoration	59	59 (49–70)	15.6	23.6 (20.2–27.0)
Habitat restoration + tree damage from wildlife	59	-	22.0	-
NWFPs	58	-	28.1	-
NWFPs + habitat restoration	58	-	15.8	-
Flooding	55	-	29.2	-
Flooding with subtropical plantations	71	-	11.1	-
Flooding with temperate plantations	80	-	8.6	-
Landslides	58	-	28.2	-
Landslides with subtropical plantations	74	-	10.0	-
Landslides with temperate plantations	83	-	7.5	-

	Population in 2041		Fallow land in 2041 (hectare)	
Scenario	**SD**	**ABM**	**SD**	**ABM**
Urban income increase	52	52 (42–62)	30.2	31.5 (28.0 -35.0)
Urban income increases with subtropical plantations	66	66 (56–77)	12.9	12.8 (9.2–15.8)
Urban income increases with temperate plantations	74	77 (69–84)	10.9	9.9 (7.0–12.8)

4.3 Benefits of Tree Planting May Be Greater in Locations That Are Vulnerable and Exposed to Flooding or Landslides

As demonstrated by the outputs of the spatial analysis, water retention increases when trees are planted (Appendix C). This supports our assumptions that fewer landslides will occur and that flooding will be less intense when trees are planted. More village-specific data would be needed to quantify the extent to which flood and landslide impacts could be reduced for a particular community.

Because trees increase water retention and stabilize soil, they can reduce climate damages and improve rural livelihoods in disaster-prone areas. Our analysis shows that trees are a cost-effective climate adaptation strategy in Bhutan. For example, when considering flood and landslide impacts, the value of trees increases. Avoiding one landslide increases the benefit-to-cost ratio of plantations from 18.6 to 19.1 in subtropical areas and from 30.5 to 31.1 in temperate regions (Table 2). Similarly, reducing flood damages by 30% results in benefit-to-cost ratios of 19.0 and 31.0 in subtropical and temperate regions, respectively (Table 2). This is because in vulnerable and exposed locations, trees provide value not only via plantation production, but also by reducing crop loss. These climate adaptation benefits show that in addition to the value of plantation products, trees can increase resilience to extreme events.

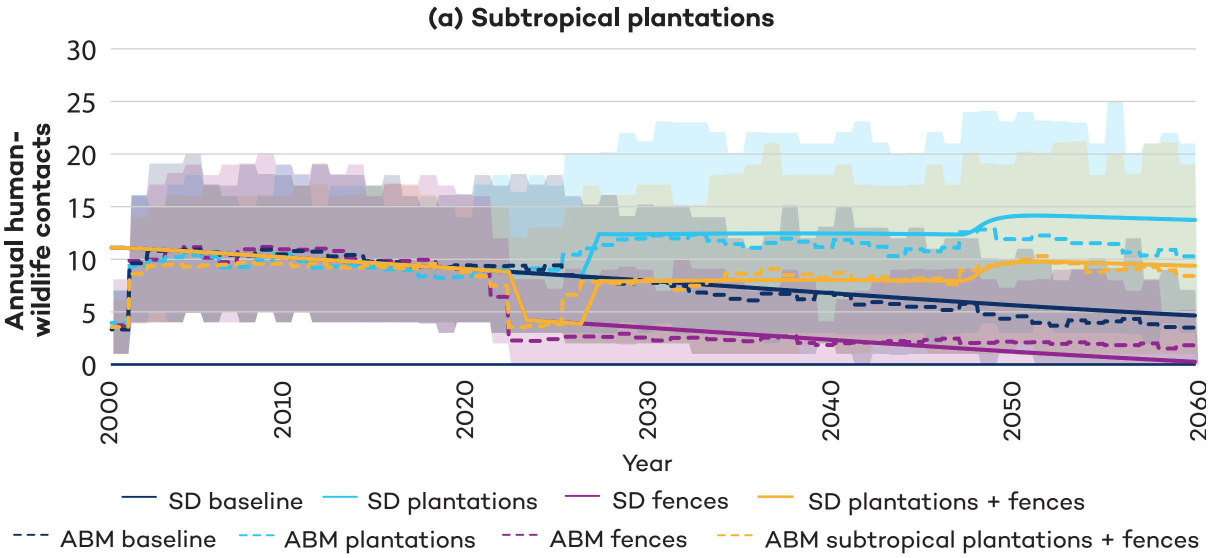
4.4 Plantations Increase Human–Wildlife Conflict but Create More Value Than Fences

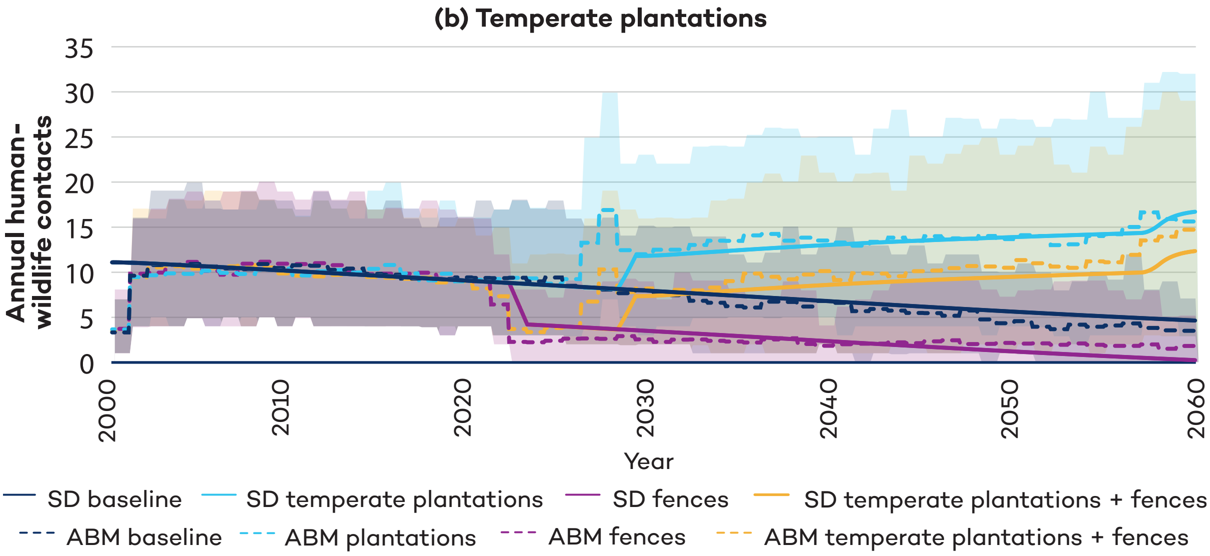
The InVEST models show that tree planting improves habitat quality (Appendix C). This supports our assumption that fruit trees attract wild animals, which means that there are more human–wildlife contacts when trees are planted than in the baseline scenario (Figure 6). This leads to more losses from wildlife. However, the income from plantations more than offsets these losses, so net household income is greater than in the baseline scenario, as indicated in Table 2.

Unlike plantations, fences reduce the number of human–wildlife contacts. Combined with construction jobs, this increases household income, but the cost to build and maintain this grey infrastructure is only slightly more than this increase. Thus, fences have a benefit-to-cost ratio of only 1.4 (Table 2), and they do not have noticeable impacts on income (Figure 3), population (Figure 4), or fallow land (Figure 5).

Our models assume that income is the only direct impact on the decision to migrate. Human–wildlife conflict factors into the decision only to the extent that it affects income. However, human–wildlife conflict is reported as an important factor in the decision to leave rural areas (National Statistics Bureau of Bhutan, 2018b). Thus, the impact of fences on reducing rural–urban migration may be larger than what we have estimated. If this is the case, then it is possible that fences combined with plantations would produce more value than plantations alone.

Figure 6. Number of human–wildlife contacts under the baseline, plantations, fences, and fences + plantations scenarios. Fences can mitigate human–wildlife conflict, unlike plantations, which attract wildlife. Shading indicates the 10th and 90th percentiles of the ABM results. Figure extends beyond the 20-year time horizon that is most relevant for decision making to show the effect of harvesting timber.





Source: Authors' diagram.

4.5 NWFPs Provide Additional Income but Increase Human–Wildlife Conflict

Gathering NWFPs is a practice that has become popular in some parts of Bhutan. In a scenario in which people gather NWFPs as an additional source of income, we estimate that these products generate a total of USD 8,027 over 20 years.

However, because NWFPs are also important food sources for many animals, depleting these resources increases human–wildlife conflict. Thus, although gathering these products temporarily increases per capita income, cumulative household income over 2022–2041 is lower than in the baseline scenario with no NWFPs (Tables 2 and 3).

Habitat restoration can mitigate some human–wildlife conflict. This raises cumulative household income by USD 21,300, but this is still lower than the USD 31,100 required to plant and maintain the trees.

4.6 Nurseries Reduce Costs and Create Income

Nurseries reduce planting costs and create jobs for residents, and so increase the net benefits of tree planting (Tables 2 and 3). Furthermore, wages from maintaining nurseries reduce rural–urban migration, which leads to less fallow land (Table 4).

However, there is also a cost to establishing and maintaining nurseries. Specifically, a single subtropical nursery costs BTN 460,000 (USD 5,980) to create and BTN 1.28 million (USD 16,640) per year to maintain. In temperate regions, these costs are BTN 445,000 (USD 5,785) upfront and annual maintenance of BTN 1.02 million (USD 13,260). These nurseries are designed to accommodate 100,000 seedlings planted per year.

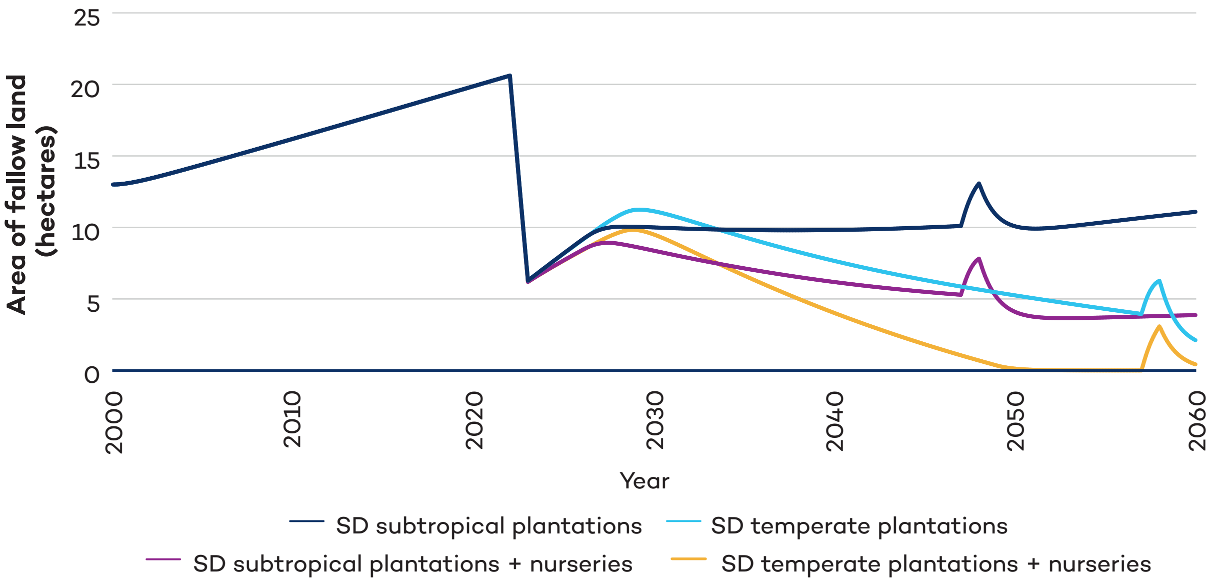
In this assessment, we simulate dynamics in a single village. We assume that approximately 10,000 trees are planted. Thus, one village uses only a fraction of the seedlings from a single nursery. To calculate costs and benefits of using nurseries, we scale the costs of establishing and maintaining nurseries and the number of jobs created in nurseries by the share of seedlings that are used in the village-level model. This results in higher net benefits and a larger benefit-to-cost ratio than when plantations are established without nurseries (Table 5). This is primarily due to cost savings, so impacts on other outputs are very small.

Table 5. Net benefits and benefit-to-cost ratio of plantations with and without nurseries. Nurseries reduce costs and create jobs, leading to an increase in net benefits and benefit-to-cost ratio.

	Net benefits (USD thousand)		Benefit-to-cost ratio	
	With nurseries	Without nurseries	With nurseries	Without nurseries
Subtropical	475.9	272.7	23.4	18.6
Temperate	639.9	433.4	38.2	30.5

We also simulate the effect of nurseries on a single village without scaling the costs and number of jobs. This allows us to estimate the local effects of a nursery designed to serve a larger area. Specifically, wages earned in nurseries reduce rural–urban migration, leading to population growth and a decrease in fallow area. In this scenario, the area of fallow land may decline to 0 (Figure 7). If this happens, there could be a shortage of land, which may limit agricultural production or lead to deforestation. Thus, it is important to consider the capacity of villages to accommodate these impacts, as well as access to a broader market for seedlings, before selecting locations for nurseries.

Figure 7. Area of fallow land in locations with and without nurseries. Fallow land decreases in places with nurseries because jobs in nurseries attract more people, which requires expansion of agricultural land.



Source: Authors' diagram.

4.7 Tree Planting May Be Less Effective at Slowing Migration in Places Where Pressure to Leave Is Very Strong

When considering a scenario in which urban income increases, there is more pressure to leave rural areas. Thus, as expected, population is smaller and there is more fallow land at the end of the simulation (Table 4). Tree planting can reduce migration, but the benefit-to-cost ratio is smaller than when urban income is constant (Tables 2 and 3). This suggests that although plantations can counter some undesired outcomes, there is a limit to their ability to slow rural–urban migration. Thus, they may be less effective in places where the pressure to migrate is very strong.

4.8 Plantations Are Financially Superior to Fences

Our calculations of the NPV and IRR show that tree planting is financially superior to the grey infrastructure alternative of building fences. This is true even though we discount the value of future benefits and include the opportunity cost of financing plantations instead of making alternative investments. Specifically, the NPV of subtropical plantations ranges from USD 186,000 to USD 196,000, depending on whether the opportunity cost is included, and the NPV of temperate plantations ranges from USD 292,000 to USD 305,000 (Table 6).

The IRR of subtropical plantations is slightly larger than the IRR of temperate plantations even though the net benefits, benefit-to-cost ratio, and NPV of temperate plantations are more than 50% larger than those in subtropical regions. The larger NPV, net benefits, and benefit-to-cost ratio of temperate plantations are because they produce more fruit and more valuable fruit than subtropical trees. Conversely, the smaller IRR of temperate plantations is because they take longer to mature than subtropical plantations. Specifically, in the plantations scenario, cash flows are negative until 2028 in temperate regions, but in subtropical regions, cash flows become positive in 2026. The delay in positive cash flows results in a lower IRR.

The NPV of plantations is approximately 100 times larger than the NPV of fences. Furthermore, the IRR of fences is 25.2%, compared to an IRR of over 40% for plantations.

Fences combined with plantations are slightly less financially attractive than plantations on their own. However, because we may be underestimating the impact of fences on migration (see Section 4.4), it may be that the hybrid strategy of plantations combined with fences is the most effective way to support rural livelihoods.

Table 6. Financial analysis results

	Subtropical plantations	Temperate plantations	Fences	Fences with subtropical plantations	Fences with temperate plantations
FINANCIAL INDICATORS					
NPV without opportunity cost (USD)	196,039	304,900	2,548	198,576	307,439
NPV with opportunity cost (USD)	186,452	291,918	-1,701	184,740	290,209
IRR without opportunity cost	45.8%	43.5%	25.2%	44.9%	42.9%
IRR with opportunity cost	37.3%	35.6%	2.0%	34.3%	33.6%

* N/A indicates that these IRR values are negative and cannot be calculated by Excel

4.8.1 Financial Impact on Government Agencies

For the Million Trees Initiative, timber plantations will be planted on public land, and consequently, timber value will translate to government revenue (with some accruing to the local community in the form of harvesting wages). The present value of 6 hectares of timber plantations is USD 1,257 (USD 209.5 per hectare) in subtropical regions and USD 923 (USD 153.8 per hectare) in temperate regions (Table 6). Additionally, assuming 114 t CO_2 stored per hectare and a value of USD 2.5 per ton of CO_2, each hectare of timber plantation could earn an additional USD 285 in carbon credits (Måren & Sharma, 2021; Nordhaus, 2017).

We also note that the present value of the capital and maintenance costs of timber plantations is larger than the present value of timber revenue. Specifically, the cost to plant 1 hectare of timber is USD 643 (USD 321 using seedlings from nurseries), and the present value of maintenance costs for 5 years is USD 1,363 in subtropical regions and USD 858.5 in temperate regions. Thus, the present value of the monetary costs of timber plantations is approximately 7–10 times the present value of the revenue that can be earned. Carbon credits could increase government revenue, but it would still be necessary to consider other benefits to justify the investment on financial terms.

For example, strategically locating timber plantations to mitigate flooding and landslides could have additional benefits. In this assessment, we have quantified only natural disaster impacts on agricultural production because we are considering a rural area with minimal public services. These household benefits improve the economic viability of plantations. In more built-up areas, avoided floods and landslides could also result in avoided infrastructure damage, which may translate to cost savings for the government. This highlights that both public and private stakeholders can benefit from strategic tree planting.

5.0 Conclusions

With the high net benefits, benefit-to-cost ratio, NPV, and IRR of plantations, it may be surprising that more plantations have not already been established. However, it is important to recognize that the only benefits included in this assessment are household income and government revenue far in the future. Thus, plantations are an effective way to support rural livelihoods, but investors may not directly benefit.

The results further suggest that it may be beneficial for landowners to purchase seedlings themselves and plant them on their own property. However, this would require additional capacity at the local level. Thus, the Million Trees Initiative, which includes local capacity-building activities, may be able to motivate tree planting and land restoration beyond what is currently planned. Furthermore, the results of this assessment may help generate local buy-in.

Expanding tree planting across rural Bhutan would have large economic benefits for rural communities. Plantation products create an important source of income for farmers. Improving rural livelihoods can slow rural–urban migration and increase utilization of arable land. Restoring degraded and fallow land can also reduce flooding and landslides. In this way, tree planting would reduce the exposure of people and the government to extreme precipitation. The climate adaptation benefits combined with the direct economic impacts of plantations make tree planting a valuable undertaking in Bhutan.

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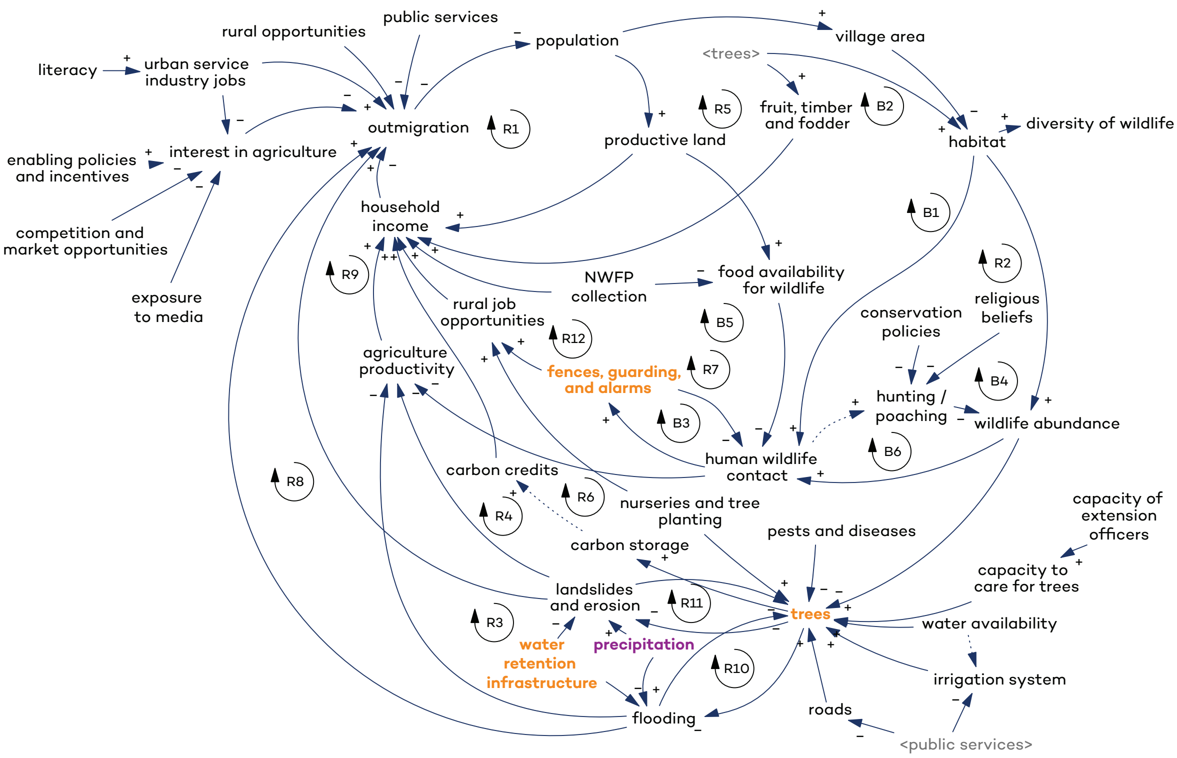
Appendix A. Full Causal Loop Diagram

In the full causal loop diagram (Figure A1), we include additional variables and relations, beyond those in Figure 1, that provide context for planting trees in rural Bhutan.

Figure A1. Full causal loop diagram



Source: Authors' diagram.

Considering the initial causes of outmigration, an increase in literacy and formal education has increased opportunities for service industry jobs in urban areas. With limited rural job opportunities and few public services, urban locations have become more attractive. Furthermore, competition for market opportunities, a decline in policies that incentivize agriculture, steep farmland that is unfavourable for mechanized farming, and exposure to urban life via television and other media, make agriculture less desirable.

With population decrease, there is less productive land and, therefore, less agricultural field area. For this reason, wildlife that prefer agricultural crops may come closer to human settlements looking for food, which increases human–wildlife conflict. This creates an additional feedback loop that may help explain observed population loss:

- **R7:** The loss of population reduces productive land, which decreases food available for wildlife and so leads to more human–wildlife conflict. This decreases agricultural production, which reduces household income and motivates emigration, leading to further population decline.

The dynamics triggered by tree planting extend beyond what is shown in Figure 1. For example, flooding and landslides/erosion increase migration directly, as it is easier to leave a place that experiences frequent natural disasters. This creates the following reinforcing feedbacks when trees are planted:

- **R8:** Trees mitigate flooding, which decreases migration, leading to population growth. This requires more village area, which destroys habitat and reduces wildlife abundance. Because wildlife may be a threat to saplings, more trees survive and further reduce flooding.
- **R9:** The same as R8 but focusing on the impact of trees on landslides and erosion, instead of flooding.

Flooding and landslides/erosion are also direct threats to tree survival. This leads to two more feedbacks:

- **R10:** Trees mitigate flooding. With fewer floods, more trees survive.
- **R11:** Trees reduce landslides/erosion, which are a threat to tree survival.

Other threats to tree survival include pests and disease, water availability, accessibility via roads, the capacity of people to care for trees, and the capacity for extension officers to provide training. Limited water availability makes irrigation necessary but also makes irrigation more challenging. The lack of public services may impact the presence of roads and irrigation, creating additional challenges for tree planting.

In response to human–wildlife conflict, many villages use fences, guarding, and alarms, which creates a balancing feedback loop:

- **B3:** Human–wildlife contact motivates fences, guarding, and alarms. These interventions reduce human–wildlife contact, which lessens the need for fences, guarding, and alarms.

It is possible that these interventions could create jobs and household income, leading to three new feedback loops:

- **R12:** Human–wildlife conflict prevention creates jobs and income, so population increases, requiring more village area. This reduces habitat, leading to more human–wildlife contact, thus creating more jobs from fences, guarding, and alarms.
- **B4:** Income from jobs for addressing human–wildlife contact attracts more population, which encroaches on habitat. This leads to lower abundance of wildlife and less contact between humans and wildlife, so there are fewer jobs for fences, guarding, and alarms.
- **B5:** With population decrease, there is a loss in productive land, and so there is less food available for wildlife. The resulting increase in human–wildlife conflict creates jobs from fences, guarding, and alarms. This increases household income, which slows migration and population loss.

As with R2 and B1, which of these feedback loops is triggered in a specific location depends on the food preferences of wildlife. We also note that the loss of habitat affects not only wildlife abundance but also wildlife diversity.

Although there is not much retaliatory killing of wildlife in Bhutan due to conservation policies and religious beliefs, it is possible. This could create a balancing feedback loop:

- **B6:** Human–wildlife contact leads to more hunting/poaching, which reduces wildlife abundance. This leads to less human–wildlife contact.

Appendix B. Simulation Model Assumptions and Inputs

System Dynamics Model

The system dynamics (SD) model simulates population, land cover, and household income under a wide range of scenarios.

Population changes in response to births, deaths, and migration. The birth rate decreases over time, while the death rate is roughly constant, with small annual variations (National Statistics Bureau of Bhutan, 2018a, 2019). Migration depends on the ratio between per capita income earned in rural areas and the average per capita income that could be earned in urban areas. When this ratio is equal to 1, there is no migration. If the ratio is less than 1, there is migration to urban areas, and when the ratio is greater than 1, there is net migration into the rural area.

Land is classified as either agricultural land, fallow land, plantation area, secondary forest, or forest. When population shrinks, agricultural land is left fallow. When population grows, fallow land and/or forest is converted to productive cropland.

People earn income from agricultural production, non-wood forest products (NWFPs), fence construction, and tree planting and production.

Agricultural income depends on the area of land under cultivation, the value produced per hectare, and the costs of production per hectare.

Floods and landslides reduce agricultural revenue. We assume that flooding occurs every 5 years. If trees are not planted, agricultural production is reduced by 10% in years with flooding. If trees are planted, the reduction is only 7%.

We assume that the number of landslides over the course of the entire simulation depends on whether trees are planted. Each landslide reduces agricultural revenue by a fixed percentage when the landslide occurs and by a smaller percentage for several years after the landslide. After 4 years, recovery is complete.

Human–wildlife conflict also reduces agricultural income, and we simulate crop damage from wild herbivores. The abundance of wildlife changes as the forest area changes (more forest in the study area means more animals in the study area and vice versa). The number of human–wildlife contacts per animal per year depends on the area of agricultural land and fruit plantations compared to the area of forest and density of NWFPs in the forest. Each contact incurs a cost.

The number of annual contacts can be reduced by building electric fences, which also reduce the need to guard fields from wildlife (United Nations Development Programme, 2016). Building fences creates jobs, which are an additional source of household income. We assume that the number of jobs created to maintain fences would be the same as the number of jobs lost due to a reduced need for guarding and so do not include maintenance wages in the assessment.

NWFPs are simulated as an aggregate, that is, we do not distinguish between different products. We assume that NWFPs grow according to an inherent growth rate that is moderated by the density of NWFPs. Some NWFPs are consumed by wildlife, and a fraction are collected by people and sold as a source of income. The fraction collected increases with population and the density of NWFPs in the forest. If the rate of NWFP collection becomes unsustainable, there may be a temporary increase in income, but ultimately the stock of NWFPs will decline, resulting in less income.

Trees can be planted as fruit or timber plantations or as habitat for wild animals. When fruit trees are mature, they produce fruit every year, which is a source of household income. Individual households must pay to maintain fruit trees. Timber trees produce value only when they are harvested. Timber trees are planted on public lands, and so timber sales provide income for the government. Trees planted in the forest do not generate value directly but do create wildlife habitat. All trees sequester carbon, which may provide a source of income in the form of carbon credits.

We assume that until trees reach maturity, 4% die each year. However, it is possible that the survival rate will decrease if there are a lot of wild animals that destroy seedlings. For this reason, we simulate an alternative scenario where the seedling survival rate decreases when the density of wildlife in the forest increases.

If nurseries are established, seedlings from nurseries will be used for tree planting. This lowers the costs of tree planting and creates jobs in nurseries.

Table B1 lists the model inputs used for this analysis.

Table B1. Numerical inputs for the SD model.

Variable name	Unit	Value	Assumptions, notes, and sources
Population inputs			
Initial population	People	100	Assumed. Using a value of 100 allows us to easily consider percent change in population within the study area.
Birth rate	1/1,000 people	Decreases from 19.7 to 11.1.	National Statistics Bureau of Bhutan (2018a) states that the crude birth rate in Bhutan was 19.7 per 1,000 people in 2005, while National Statistics Bureau of Bhutan (2019) provides estimates for the crude birth rate every 5 years from 2017 (17 per thousand people) through 2047 (11.1 per thousand people). We linearly interpolate between these data points to estimate the birth rate in each year and assume that the birth rate before 2005 is equal to 19.7 per thousand and that the birth rate after 2047 is constant at 11.1 per thousand.

Variable name	Unit	Value	Assumptions, notes, and sources
Death rate	1/1,000 people	Between 6.7 and 8.4	National Statistics Bureau of Bhutan (2018a) states that the crude death rate in Bhutan was 7.1 per thousand people in 2005, while the National Statistics Bureau of Bhutan (2019) provides estimates for the crude death rate every 5 years from 2017 (7.1 per thousand people) through 2047 (8.4 per thousand people). We linearly interpolate between these data points to estimate the death rate in each year and assume that the death rate before 2005 is equal to 7.1 per thousand and that the birth rate after 2047 is constant at 8.4 per thousand.
Migration rate	1/1,000 people	-59 * income ratio + 59	Note: income ratio is equal to per capita income divided by the average per capita income that could be earned in an urban area. National Statistics Bureau of Bhutan (2018b) states that 177 people per thousand in Bhutan are at risk for internal migration. Furthermore, the maximum ratio between average household income by dzongkhag (district) is approximately four (National Statistics Bureau of Bhutan & Asian Development Bank, 2013). We, therefore, assume a maximum outmigration rate of -0.177, which is achieved when the income ratio is equal to 4. We further assume no migration when the income ratio is equal to 1 and linearly interpolate between these two points. We assume a maximum in-migration rate of 118 per thousand people, which occurs when the income ratio is -1.
Other income	USD/ person/ year	247	The average household income in dzongkhags for which at least 20% of household income comes from agriculture is approximately USD 2,126 (National Statistics Bureau of Bhutan & Asian Development Bank, 2013). From this, we estimate per capita income to be USD 500 at the start of the simulation. Based on the other model inputs, we calculate USD 264 from agriculture and USD 11 of losses from wildlife at the beginning of the simulation. This means other income must be USD 247.

Variable name	Unit	Value	Assumptions, notes, and sources
Land-use/land cover inputs			
Initial forest area	Hectare	50	Assumed
Initial agricultural land	Hectare	37	There is approximately three times as much operational land as fallow land in Bhutan (Renewable Natural Resources Statistics Division Directorate Services, 2019). We scale this to an initial area of 50 hectares of fallow and agricultural land combined.
Initial fallow land	Hectare	13	There is approximately three times as much operational land as fallow land in Bhutan (Renewable Natural Resources Statistics Division Directorate Services, 2019). We scale this to an initial area of 50 hectares of fallow and agricultural land combined.
Initial plantation area	Hectare	0	Assumed
Desired productive land per capita	Hectare/ person	0.37	Assumed based on initial population and initial agricultural area
Average agricultural revenue per hectare	USD/ hectare	2,760	National average producer price earned per kilogram of agricultural production per hectare over 2010–2018 (Food and Agriculture Organization of the United Nations, 2021)
Average expenditure per hectare of agriculture	USD/ hectare	2,046	National average expenditure across all paddy, cereal, vegetable, pulses, oilseed, mushroom, spices, and medicinal crops (Dukpa et al., 2020)

Variable name	Unit	Value	Assumptions, notes, and sources
Human–wildlife conflict inputs			
Relative attractiveness of crops, fruit, and forest areas for wildlife	-	20%	Crops are 20% more attractive than wild food. This increases by 0.01% per fruit tree planted. Equations and parameter values are calibrated using outputs from the agent-based model (ABM).
Cost per human–wildlife contact	USD/ contact	100	In rural Bhutan, approximately 0.33–18% of household income is lost to wildlife (United Nations Development Programme, 2016). Assuming losses of USD 100 per contact in our model results in household income reductions of approximately 4%, which is near the low end of reported losses. We use this low estimate because we consider only crop losses and do not include livestock depredation.
Percent reduction in number of human–wildlife contacts due to fences	Contacts/ year/km	1.5	Calibrated from output of ABM
Labour income per km of fencing built	USD/km	300	BTN 92.72 million was spent to construct 1,236 km of electric fences (United Nations Development Programme, 2016). This corresponds to BTN 75,016 per km, which is USD 1 per km, assuming an exchange rate of USD 0.013 per BTN. Of this total, 60% is required for labour, poles, and transportation (United Nations Development Programme, 2016). From this, we estimate that labour comprises 30% of the total costs.
Initial wildlife abundance	Animals	25	Assumed
Impact of forest area on wildlife abundance	Animals/ hectare	0.3	We assume that for each hectare of wildlife habitat gained/lost, the number of wildlife will increase/decrease by 0.3 animals.

Variable name	Unit	Value	Assumptions, notes, and sources
Cost to construct fences	USD/km	1,000	BTN 92.72 million was spent to construct 1,236 km of electric fences (United Nations Development Programme, 2016). This corresponds to BTN 75,016 per km, which is USD 1,000 per km, assuming an exchange rate of USD 0.013 per BTN.
Cost to maintain fences	USD/km/year	100	Assumed 10% of construction costs
Flooding and landslide inputs			
Flood frequency	1/year	5	Assumed
Share of annual productivity lost due to one landslide	Percent	10	Assumed
Reduction in productivity loss if trees are planted	Percent	30	Assumed
NWFP INPUTS			
Sustainable NWFP collection rate	Hectare/person/year	0.03	Assumed. This value can be interpreted as the share of NWFPs in one hectare that one person can collect each year.
NWFP market value	USD/kg	1.5	Assumed
Inherent NWFP growth rate	1/kg	1	Assumed
NWFP consumption rate by animals	Hectare/person/year	1.7	Assumed
Maximum NWFP density	Kg/hectare	200	Assumed

Variable name	Unit	Value	Assumptions, notes, and sources
TREE PLANTING INPUTS			
Cost to plant fruit trees without nurseries	USD/tree	Subtropical: 1.17 Temperate: 2.13	The cost to purchase and plant fruit seedlings is BTN 90 for subtropical trees and BTN 164 for temperate trees without nurseries (Pem Lama, personal communication, February 22, 2022). Assuming a conversion rate of USD 0.013 per BTN, we get USD 1.17 per subtropical tree and USD 2.13 per temperate tree. We assume trees planted to restore habitat cost the same as timber trees.
Cost to plant fruit trees with nurseries	USD/tree	Subtropical: 0.69 Temperate: 1.05	The average cost to purchase and plant fruit seedlings is BTN 53 for subtropical trees and BTN 81 for temperate trees without nurseries (Pem Lama, personal communication, February 22, 2022). Assuming a conversion rate of USD 0.013 per BTN, we get USD 0.69 per subtropical tree and USD 1.05 per temperate tree. We assume trees planted to restore habitat cost the same as timber trees.
Cost to plant timber and habitat restoration trees without nurseries	USD/tree	0.52	The cost to purchase and plant timber seedlings is BTN 40 without nurseries (Pem Lama, personal communication, February 22, 2022). Assuming a conversion rate of USD 0.013 per BTN, we get USD 0.52 per tree. We assume trees planted to restore habitat cost the same as timber trees.
Cost to plant timber and habitat restoration trees with nurseries	USD/tree	0.26	The cost to purchase and plant timber seedlings is BTN 20 with nurseries (Pem Lama, personal communication, February 22, 2022). Assuming a conversion rate of USD 0.013 per BTN, we get USD 0.26 per tree. We assume trees planted to restore habitat cost the same as timber trees.
Time for fruit trees to mature	year	Subtropical: 4 Temperate: 6	Fruit trees take 6 years to mature in temperate regions and 4 years to mature in subtropical regions (Pem Lama, personal communication, February 22, 2022).

Variable name	Unit	Value	Assumptions, notes, and sources
Fruit produced per tree	kg/tree/year	Subtropical: 11.48 Temperate: 17.53	The Renewable Natural Resources Statistics Division Directorate Services (2019) provides national statistics on number of fruit trees and fruit production. We use these data to estimate the average production per tree across species. For subtropical regions, we use data for avocado, mango, litchi, guava, jackfruit, pomegranate, and areca nut data trees. For temperate regions, we use data for apple, apricot, plum, peach, pear, soft walnut, and persimmon trees.
Household income per kg of fruit produced	USD/kg	Subtropical: 0.77 Temperate: 0.93	The Food and Agriculture Organization of the United Nations (2021) provides the production value of many fruits in Bhutan. We use these data to estimate the average producer price per tree across species. For subtropical regions, we use data for mango, orange, guava, and areca nut data trees. For temperate regions, we use data for apple, plum, peach, pear, and soft walnut trees.
Household expenditure per fruit tree	USD/tree/year	Subtropical: 0.58 Temperate: 0.41	We assume minimal maintenance, resulting in costs of BTN 44.64 per tree in subtropical fruit plantations and BTN 31.25 per tree in temperate fruit plantations (Pem Lama, personal communication, February 22, 2022). Assuming an exchange rate of USD 0.013 per BTN, we get USD 0.58 per subtropical tree and USD 0.41 per temperate tree.
Time for timber trees to mature	year	Subtropical: 25 Temperate: 35	Timber trees take 35 years to mature in temperate regions and 25 years to mature in subtropical regions (Pem Lama, personal communication, February 22, 2022).
Timber produced per tree	ft^3/tree	301	We average the production per tree using data from teak, sal, dauabanga grandi flora, gamari, chir pine, cypress, Michelia sp., hard walnut, and oak sp (Pem Lama, personal communication, February 23, 2022).
Government revenue per m^3 of timber	USD/ft^3	1.49	Average household income per cubic foot is reported to be BTN 114.94 (Dorji, 2011). Using an exchange rate of USD 0.013 per BTN, we get USD 1.49 per ft^3.
Timber wage percent	percent	50	Assumed. Percentage of timber revenue that accrues to the local community in the form of wages.

Variable name	Unit	Value	Assumptions, notes, and sources
Timber maintenance costs	USD/tree/ year	Subtropical: 0.289 Temperate: 0.182	Using an estimate of BTN 10,000 per 450 trees per year in subtropical regions and BTN 7,000 per 500 trees in temperate regions, we get maintenance costs of BTN 22.22 per subtropical tree and BTN 14 per temperate tree (Pem Lama, personal communication, February 22, 2022). We convert to USD using an exchange rate of USD 0.013 per BTN.
Years of maintenance required for timber and habitat restoration trees	year	5	Assumed
Time for habitat trees to mature	year	Subtropical: 25 Temperate: 35	Assumed same as timber trees
Planting jobs per tree	Full-time equivalent (FTE)/tree	0	Assumed that all labour will be volunteer
Jobs for tending seedlings in one nursery	FTE/tree/ year	18	The Million Trees Initiative will create a total of 36 jobs for tending two nurseries (Pem Lama, personal communication, February 23, 2022). We, therefore, assume an average of 18 FTE in a single nursery.
Nursery and planting wages	USD/FTE	388.7	We assume a daily wage of BTN 150. With 260 working days per year and USD 0.013 per BTN, this corresponds to USD 388.7 per job annually.
Nursery planting costs	USD	Subtropical: 5,980 Temperate: 5,785	In subtropical areas, the cost to construct a nursery is BTN 400,000, the cost to purchase fruit seeds is BTN 40,000 and the cost to purchase timber seeds is BTN 20,000. This leads to a total cost of BTN 460,000. In temperate areas, the cost to construct a nursery is BTN 400,000, the cost to purchase fruit seeds is BTN 35,000 and the cost to purchase timber seeds is BTN 10,000. This leads to a total cost of BTN 445,000 (Pem Lama, personal communication, February 22, 2022). We use an exchange rate of USD 0.013 per BTN to convert these values to USD.

Variable name	Unit	Value	Assumptions, notes, and sources
Nursery maintenance costs	USD/year	Subtropical: 16,640 Temperate: 13,260	Growing seedlings in nurseries costs BTN 1 million per year in subtropical areas and BTN 800,000 in temperate areas. Other maintenance costs include the land lease (BTN 100,000 per year) and the office space rental (BTN 180,000 per year in subtropical regions and BTN 120,000 per year in temperate regions). This leads to total maintenance costs of BTN 1.28 million per year in subtropical nurseries and BTN 1.02 million in temperate nurseries (Pem Lama, personal communication, February 22, 2022). We use an exchange rate of USD 0.013 per BTN to convert these values to USD.
Nursery capacity	seedlings	100,000	Bhutan Ecological Society (personal communication, May 23, 2022)
Carbon dioxide stored per tree	t/hectare	114	Estimated based on results of Måren & Sharma (2021)
Value of carbon credits	USD/t	2.5	Social cost of carbon according to Nordhaus (2017).
Maximum annual seedling survival rate	percent	96	BES expects that 80% of planted trees will survive. Assuming 96% survival until trees reach maturity results (at which point, 100% of trees survive) in a total survival rate of 83% in subtropical regions and 81% in temperate regions.
Impact of wildlife on forest tree survival	-	-	Wildlife could damage up to 20% of trees planted in the forest (Pem Lama, personal communication, February 22, 2022). We, therefore, assume that the impact of wildlife of forest tree survival increases linearly from 0 to 0.2 as the wildlife density increases from 0 to 0.5 animals per hectare.

ABM

We use a spatial ABM to simulate how individual people and animals interact with the landscape using the NetLogo modelling environment (Wilensky, 1999). Like the SD model, the ABM estimates land cover and population changes due to tree planting and external pressures.

The ABM consists of people and wildlife that exist within a confined area and interact with the landscape. People exist in this landscape and earn income from agricultural and plantation patches. Herbivores move through the landscape in search of food.

As with the SD model, there are five land cover classes: forest, agriculture, fallow, plantation, and secondary forest. Agricultural land is organized into landholdings, which are farmed by individual households. Households are comprised of people who earn income from agriculture, tree planting, fruit production, and building/maintaining fences. In each time step, it is possible for people to die from natural causes or for new people to be born into households. When the number of people in a single household gets too large, one person will split off and form a new household with a separate landholding.

Land productivity of a particular landholding depends on the ratio between household size and agricultural area. If a household is small relative to its land, productivity is low, and some land may be fallowed. If a household is large compared to its land, productivity is high, and some fallow land or forest may be converted to agriculture. A household's agricultural income is proportional to the size and productivity of its landholding and damage from wildlife. An individual's income is the household income divided by household size.

Forest, agriculture, and plantations are all a source of food for wildlife. Wildlife move through the landscape toward locations with a higher density of food. When wildlife eat from agricultural or plantation land, the value produced by that land is decreased. Wildlife birth and death rates depend on the availability of food. Fences can be built on agricultural land to prevent wildlife from getting crops.

Trees can be planted on fallow land as either plantations or secondary forest. Unlike the SD model, the ABM assumes 100% survival. The value of fruit and timber production is split evenly among all people.

The probability that a person migrates to an urban area depends on the ratio between that individual's income and the average income that could be earned in an urban location. If income is lower than what could be earned in an urban area, the individual may emigrate. If income is higher than what could be earned in an urban area, then a new person may migrate into the household.

The landscape is a grid of "patches," where each patch is a square of a single land cover. In this model, one patch is equal to 0.25 hectares. People exist in this landscape and earn income from agricultural and plantation patches. Herbivores move through the landscape in search of food. A single patch has a specified amount of wildlife food or "energy" that can be consumed by animals. Wildlife gain energy when they eat and expend energy at each time step.

Full documentation for the model is available in the "Info" tab of the NetLogo model. Table B2 lists the parameter values used for the simulations in this report.

Table B2. Numerical inputs for the ABM

Variable name	Unit	Value	Assumptions, notes, and sources
Parameters set using the interface			
Policy start year	Year	22	Assumed to be consistent with SD model. This is the year after the simulation starts in which trees are planted and/or fences are constructed.
Area planted	Hectare	15	Assumed to be consistent with SD model. This is the area of plantations or habitat restoration when trees are planted.
Number fences	Patches	0, 30	This is the number of agricultural patches protected with fences. From 2011 through 2015, 1,236 km of electric fences were installed in Bhutan to protect 7,698 acres of land (equal to 3,115 hectares). This corresponds to 3,115 ÷ 1,236 = 2.5 hectares per km. Thus, we assume that 3 km of fencing in the SD model corresponds to 7.5 hectares or 30 patches in the SD model (United Nations Development Programme, 2016). In other words, we assume that one patch requires 0.1 km of fence.
Share plantation	-	0, 1	Assumed to be consistent with SD model. This is the share of trees planted in plantations vs. habitat restoration.
Share fruit trees	-	0.6	Assumed to be consistent with SD model. This is the share of plantation trees planted for fruit vs. timber.
Initial urban income	USD/ person	800	Assumed to be consistent with SD model. This is the annual average income that an individual could earn in an urban location in 2000.
Final urban income	USD/ person	1,000	Assumed to be consistent with SD model. This is the annual average income that an individual could earn in an urban location in 2060 if urban income increases.

Variable name	Unit	Value	Assumptions, notes, and sources
Urban income change year	Year	0, 100	Assumed to be consistent with SD model (if urban income change year = 100, urban income is constant because the simulation is shorter than 100 years).
Wildlife crop preference	-	1.2	Assumed. This is the wildlife food produced per agriculture patch relative to one forest patch.
Wildlife fruit preference	-	1.3	Assumed. This is the wildlife food produced per fruit plantation patch relative to one forest patch.
Initial number wildlife	Animals	25	Assumed to be consistent with the SD model. This is the initial number of wildlife in the simulation.
Initial population	People	100	Assumed to be consistent with the SD model. This is the initial number of people in the simulation.
Initial fallow	Patches	52	Assumed to be consistent with SD model. This is the initial number of patches that are fallow.
Simulation length	Year	60	Assumed to be consistent with SD model. This is the number of years that the simulation is run.
Subtropical	-	On, off	Assumed to be consistent with SD model. If on, values for subtropical plantations are use. If off, values for temperate plantations are used.
Fixed locations	-	Off	Assumed to be consistent with the SD model. If on, all wildlife are initialized around a pre-determined patch, and any trees are planted in the fallow area closest to the same patch. If off, wildlife are initialized in random forest locations and trees are planted on random fallow patches.

Variable name	Unit	Value	Assumptions, notes, and sources
Global variables set in the model code			
Max forest wildlife food	Energy/ patch	3	Assumed. This is the maximum amount of energy in one month that a patch of forest can supply to wildlife in a single month.
Forest growth	Energy/ patch/ month	0.5	Assumed. This is the monthly increase in energy that a patch of mature forest can supply to wildlife. If a patch is already at the maximum value, the increase is 0.
Planted forest growth	Energy/ patch/ year	0.1	Assumed. This is the monthly increase in energy that a patch of secondary forest can supply to wildlife. If a patch is already at the maximum value, the increase is 0.
Tree harvest age	Year	Subtropical: 25 Temperate: 35	Timber trees take 35 years to mature in temperate regions and 25 years to mature in subtropical regions (Pem Lama, personal communication, February 22, 2022).
Mature forest age	year	Subtropical: 25 Temperate: 35	Assumed equal to the tree harvest age. This is the time it takes for secondary forest to mature.
Ag growing months	-	March–October	Assumed. These are the months during which agriculture crops grow. In each growing month, the amount of wildlife food increases, but these patches do not produce value for people until they are harvested.
Ag harvest month	-	October	Assumed. This is the month in which agricultural patches are harvested and produce value.
Ag planting month	-	March	Assumed. This is the first month in each year in which wildlife food of agricultural patches is greater than 0.
Ag value	USD/ patch/ year	179	We multiply USD 714 per hectare (USD 2,760–USD 2,046) from the SD model by 0.25 hectares per patch. This number is the value produced by a single patch of agriculture land when harvested if the patch was not damaged by wildlife in the current year.

Variable name	Unit	Value	Assumptions, notes, and sources
Timber value	USD/ patch	138,527.3	We multiply USD 448.49 per tree (301 ft^3 per tree per year × USD 1.49 per ft^3) from the SD model by 1,235.5 trees per hectare × 0.25 hectares per patch. This number is the value produced by a single patch of mature timber plantation when harvested.
Timber wage percent	percent	50	Assumed. Percentage of timber revenue that accrues to the local community in the form of wages.
Fruit value	USD/ patch/ year	Subtropical: 611.7 Temperate: 1,128.16	We multiply USD 8.84 per subtropical tree per year (11.48 kg per tree per year × USD 0.77 per kg) and USD 16.30 per temperate tree per year (17.53 kg per tree per year × USD 0.93 per kg) from the SD model by 276.8 trees per hectare × 0.25 hectares per patch. This number is the value produced by a single patch of mature fruit plantation when harvested, assuming no wildlife damage.
Fruit maintenance cost	USD/ patch/ month	Subtropical: 3.35 Temperate: 2.34	We multiply BTN 44.64 per subtropical tree per year and BTN 31.25 per temperate tree per year from the SD model by 276.8 trees per hectare × 0.25 hectares per patch ÷ 12 months per year × USD 0.013 per BTN. Every month after fruit trees are planted, this value is subtracted from the income of individuals.
Fruit harvest month	-	November	Assumed. This is the month in which the fruit value is realized.
Fruit harvest age	Year	Subtropical: 4 Temperate: 6	Fruit trees take 6 years to mature in temperate regions and 4 years to mature in subtropical regions (Pem Lama, personal communication, February 22, 2022).
Damage per contact	percent	100	Assumed. In each year, the value produced by an agriculture or fruit plantation patch that is damaged by wildlife is reduced by this percent.
Max household size	People	9	The average rural household size in Bhutan is 4.4 (National Statistics Bureau of Bhutan, 2017). Because some households will be smaller and some will be larger, we assume a maximum household size of nine. When a household has more than nine people, one person splits off to form a new household. With this assumption, the average household size stays roughly between three and six throughout the simulation.

Variable name	Unit	Value	Assumptions, notes, and sources
Construction wages	USD/ FTE	300	This value is the income earned by individuals who help build fences. The value is assumed so that when multiplied by the FTE per fence patch, we get USD 30 per fence patch. Because we assume that one fence patch is equivalent to 0.1 km of fencing, this corresponds to USD 300 per km, which is consistent with the SD model.
FTE per fence patch	FTE/ fence patch	0.1	This is the number of individuals who earn construction wages per fence patch. One fence patch is defined as an agricultural patch that has fence on it and is assumed to be equivalent to 0.1 km of fence. The FTE/ fence patch value is assumed so that when multiplied by the construction wages, we get USD 30 per fence patch to be consistent with the SD model.
Other income	USD/ person/ month	20.58	Using information from National Statistics Bureau of Bhutan & Asian Development Bank, (2013), we estimate annual additional income of USD 247 per person. We divide by 12 to get an average additional income per month. We assume that every individual earns this much income every month on top of any other wages earned.

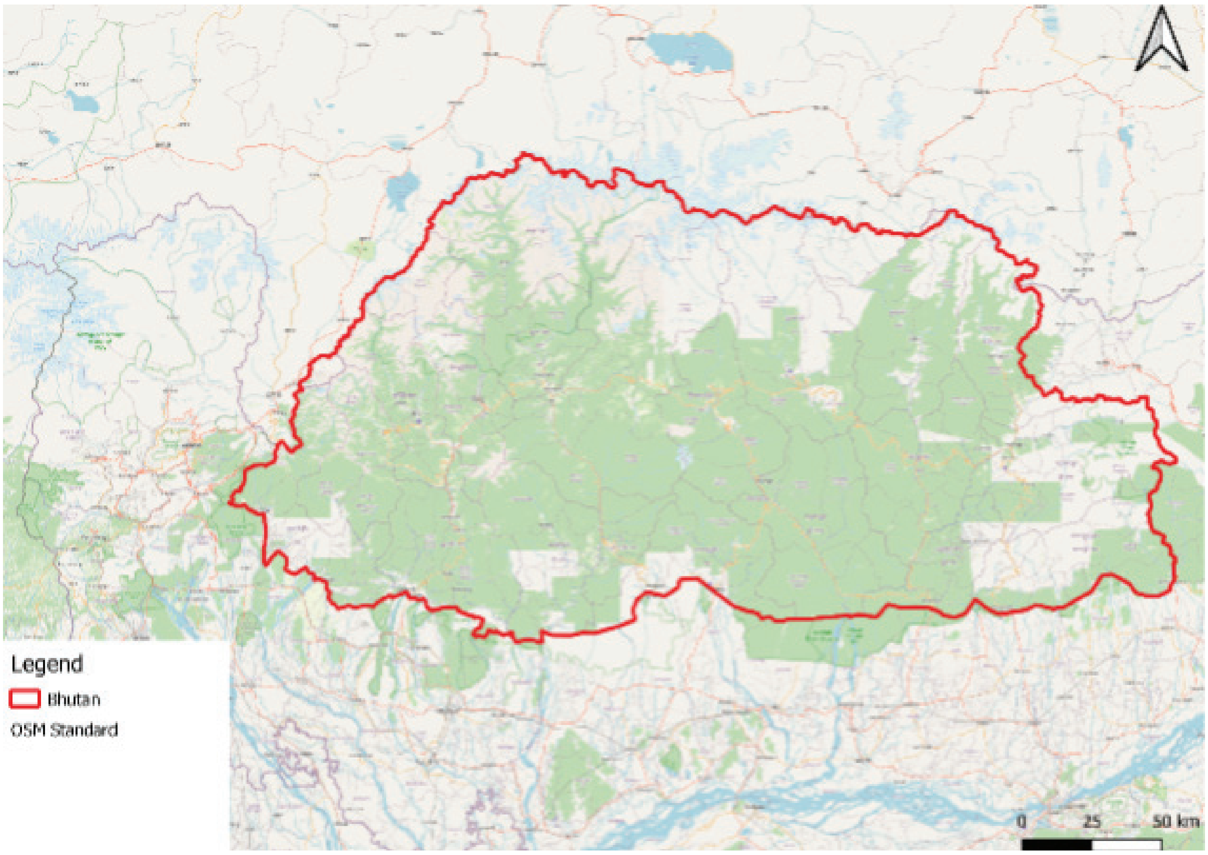
Appendix C. Spatial Analysis Report

C1. Model Setup

C1.1 Study Area

The study area of this analysis is the state of Bhutan (Figure C1).

Figure C1. Location of Bhutan



Source: Authors' diagram created using data from OpenStreetMap (© OpenStreetMap contributors, https://www.openstreetmap.org/copyright).

C1.2 Coordination System

Based on the world project coordinate system called "V WGS 84 / Pseudo-Mercator – Spherical Mercator – ESPG: 3857"

Here is the detail of the coordinate system:

```
PROJCS["WGS 84 / Pseudo-Mercator",
  GEOGCS["WGS 84",
    DATUM["WGS_1984",
      SPHEROID["WGS 84",6378137,298.257223563,
        AUTHORITY["EPSG","7030"]],
      AUTHORITY["EPSG","6326"]],
    PRIMEM["Greenwich",0,
      AUTHORITY["EPSG","8901"]],
    UNIT["degree",0.0174532925199433,
      AUTHORITY["EPSG","9122"]],
    AUTHORITY["EPSG","4326"]],
  PROJECTION["Mercator_1SP"],
  PARAMETER["central_meridian",0],
  PARAMETER["scale_factor",1],
  PARAMETER["false_easting",0],
  PARAMETER["false_northing",0],
  UNIT["metre",1,
    AUTHORITY["EPSG","9001"]],
  AXIS["X",EAST],
  AXIS["Y",NORTH],
  EXTENSION["PROJ4","+proj=merc +a=6378137 +b=6378137 +lat_ts=0.0 +lon_0=0.0 +x_0=0.0 +y_0=0 +k=1.0 +units=m 
+nadgrids=@null +wktext  +no_defs"],
  AUTHORITY["EPSG","3857"]]
```

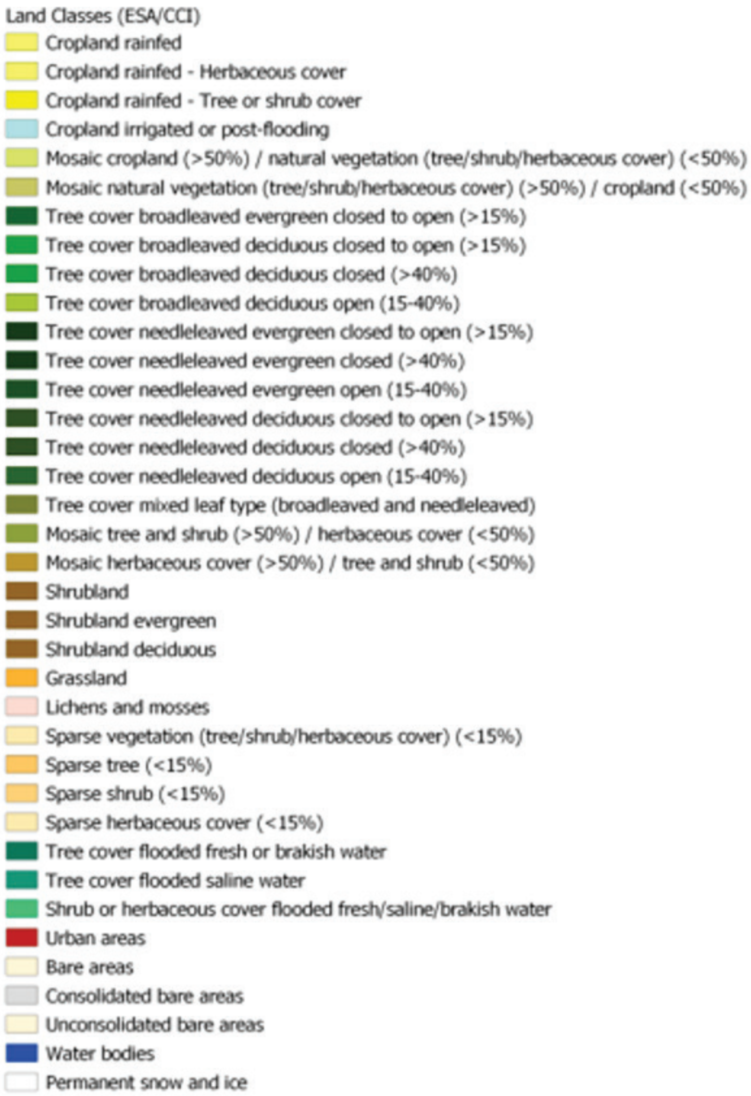
C1.3. Land Cover Maps—European Space Agency Climate Change Initiative—Land Cover Project

The global land cover maps developed by the European Space Agency Climate Change Initiative – Land Cover (ESA/CCI-LC) have been used for this study (ESA/CCI-LC, n.d.). The maps have a spatial resolution of 300m per pixel, and they show the different land cover classes in 1992, 2000, 2010, and 2015.

- The dataset (Figure C2) has originally 37 land cover classes and it can be downloaded from http://maps.elie.ucl.ac.be/CCI/viewer/index.php
- The product technical report is available under http://maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf.
- The descriptions of the land classes can be found here: http://maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-QuickUserGuide-LC-Maps_v2-0-7.pdf.

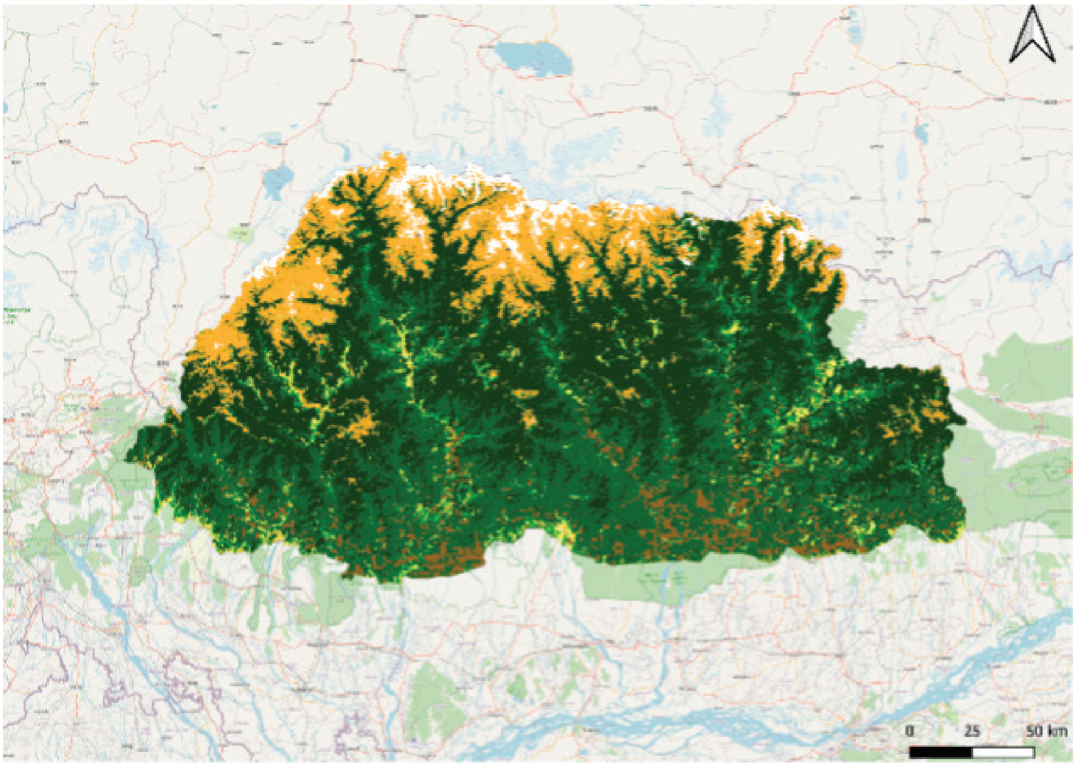
Figures C3, C4, C5, and C6 show the land cover of Bhutan in 1992, 2000, 2010, and 2015.

Figure C2. Land cover classes of the land-use/land cover (LULC) map developed in 2015 by ESA/CCI-LC



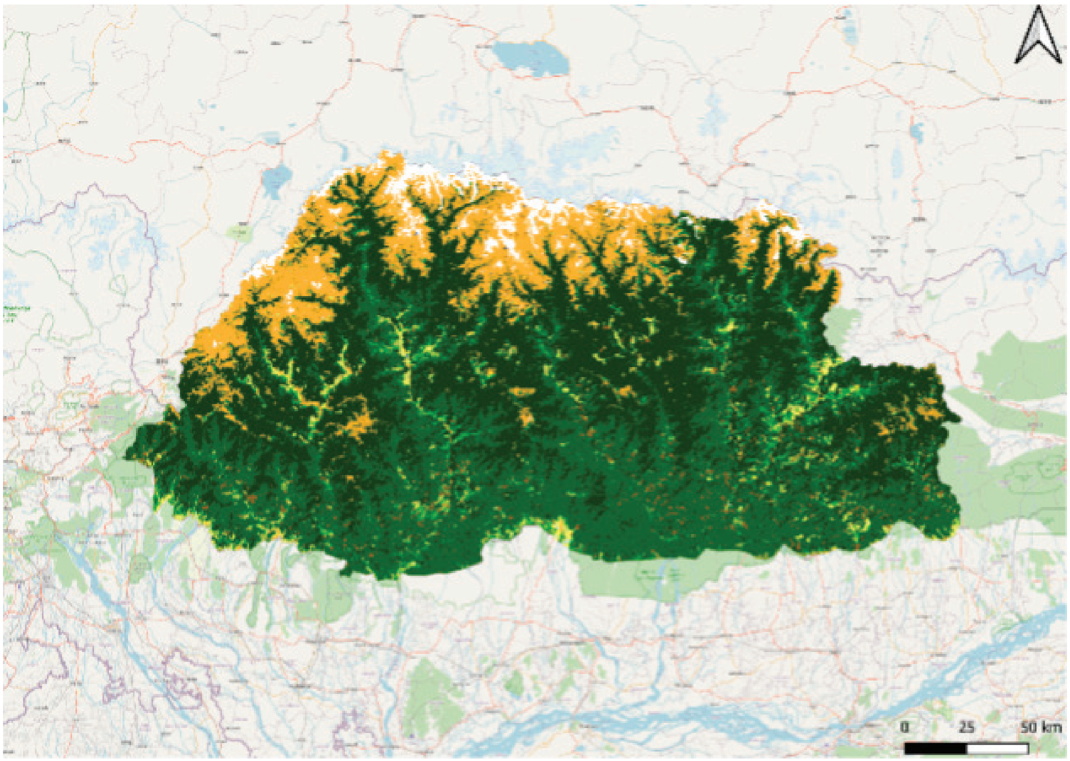
Source: Authors' diagram.

Figure C3. LULC 1992



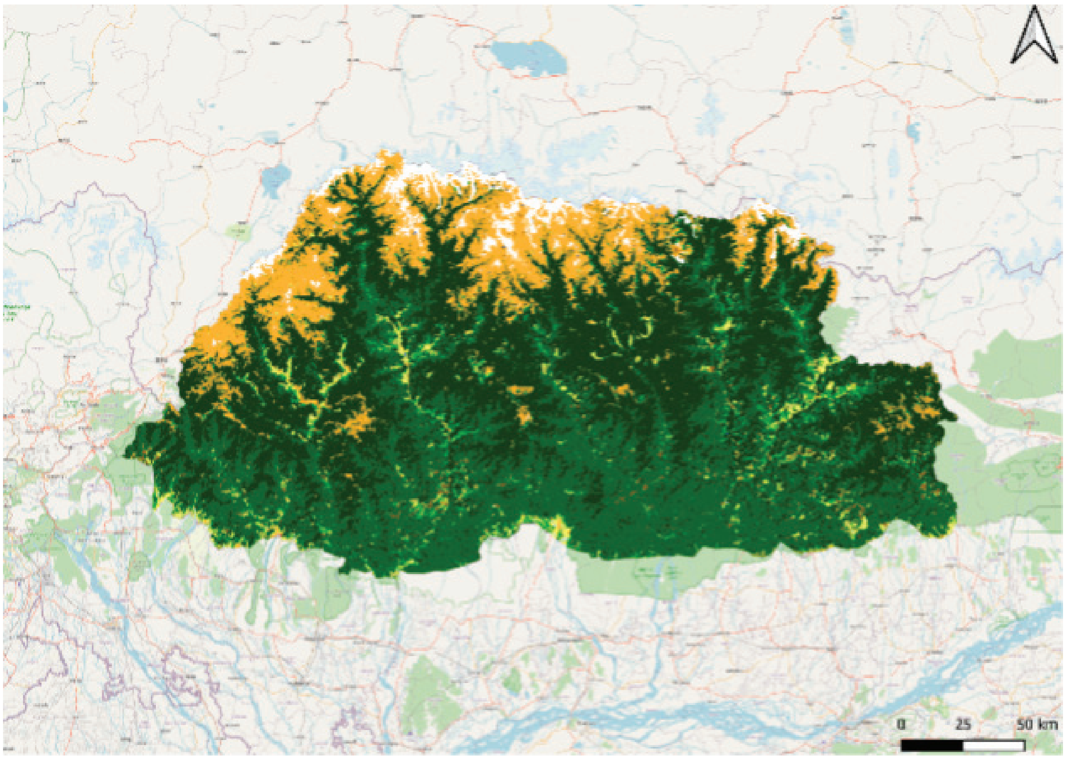
Source: Authors' diagram based on data from ESA/CCI-LC and OpenStreetMap (© OpenStreetMap contributors, https://www.openstreetmap.org/copyright).

Figure C4. LULC 2000



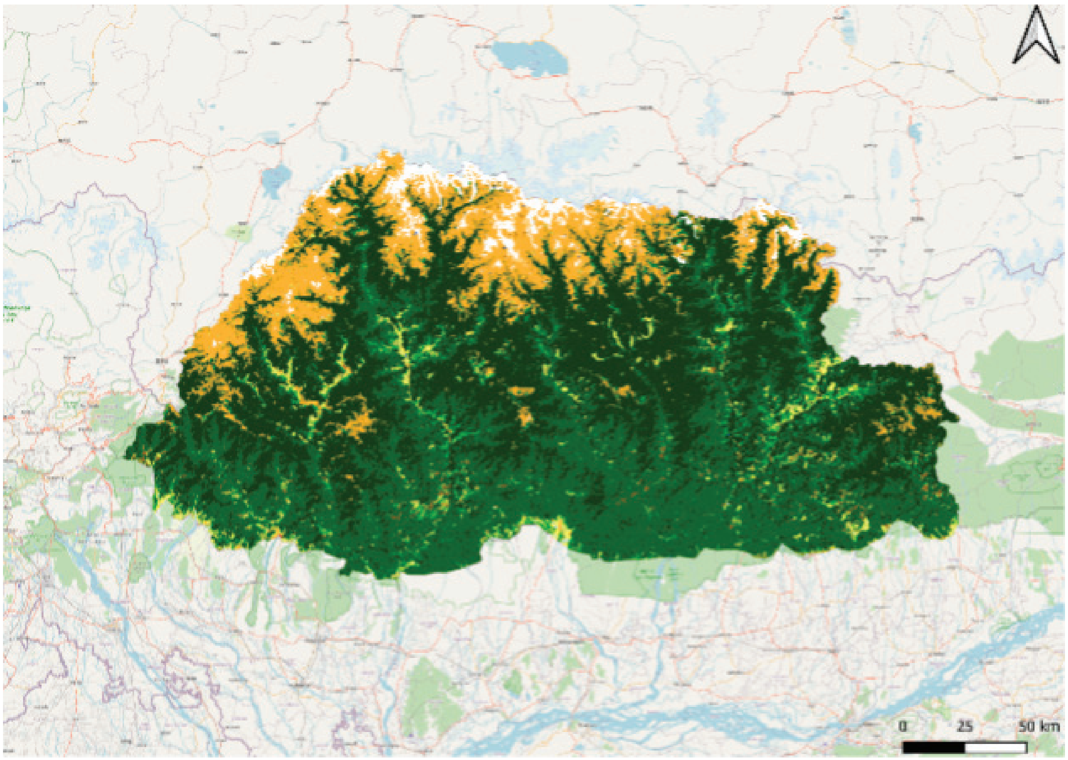
Source: Authors' diagram based on data from ESA/CCI-LC and OpenStreetMap (© OpenStreetMap contributors, https://www.openstreetmap.org/copyright).

Figure C5. LULC 2010



Source: Authors' diagram based on data from ESA/CCI-LC and OpenStreetMap (© OpenStreetMap contributors, https://www.openstreetmap.org/copyright).

Figure C6. LULC 2015



Source: Authors' diagram based on data from ESA/CCI-LC and OpenStreetMap (© OpenStreetMap contributors, https://www.openstreetmap.org/copyright).

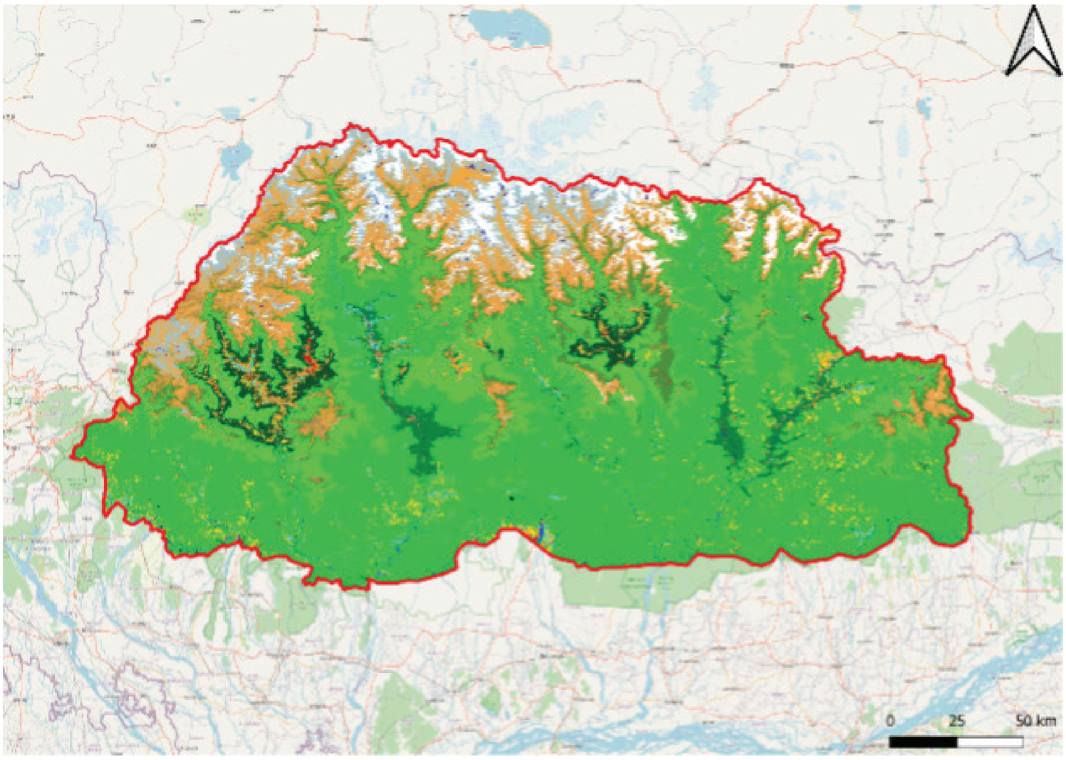
C1.4 Land Cover Maps—LULC 2016

Another map from another source (Forest Resources and Management Division of the Department of Forests and Park Services, 2016) classifies the land cover using land classes that are different from the LULC maps developed by ESA/CCI-LC. This LULC map illustrates Bhutan as of 2016 (Figure C8). Figure C7 shows the legend of the LULC 2016 map. It should be noted that the resolution of this LULC is 50 m (originally it was 10 m, but we decreased it because InVEST required many hours to run).

Figure C7. Legend LULC map 2016

Source: Authors' diagram.

Figure C8. LULC 2016



Source: Authors' diagram based on data from Forest Resources and Management Division of the Department of Forests and Park Services (2016) and OpenStreetMap (© OpenStreetMap contributors, https://www.openstreetmap.org/copyright).

C1.5 Software and Simulation

The ecosystem services map simulation has been performed using InVEST Software V.3.9.0 (https://naturalcapitalproject.stanford.edu/invest/). The spatial input data for the InVEST model have been prepared by utilizing QGIS-OSGeoW-3.4.2-1 (qgis.org/downloads/). The tabulated data will be managed and prepared in MS Excel V. 2016.

C2 Carbon Storage

C2.1 Input Data Preparation and Processing—ESA/CCI-LC Maps

1. **LULC maps:** See Section C1.4
2. **Carbon Pools:** Table of LULC classes, containing data on carbon stored in each of the four fundamental pools for each LULC class.
    - Carbon above ground: The values of carbon density in aboveground mass (Mg/ha or tons/ha) of each land-use type are shown in Table C1.
    - Carbon below ground: The values of carbon density in belowground mass (Mg/ha) of each land-use type are shown in Table C1.

- Carbon stored in organic matter: The values of carbon density in dead mass (Mg/ha) of each land-use type are shown in Table C1.
- Carbon stored in soil: The values of carbon density in dead mass (Mg/ha) of each land-use type are shown in Table C1.

The unit of measurement for these coefficients is Mg/ha. Average carbon coefficients values have been found in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories report, Chapter 4 "Agriculture, Forestry and Other Land Use" (IPCC, 2006).

Table C1. Carbon pools ESA/CCI-LC maps

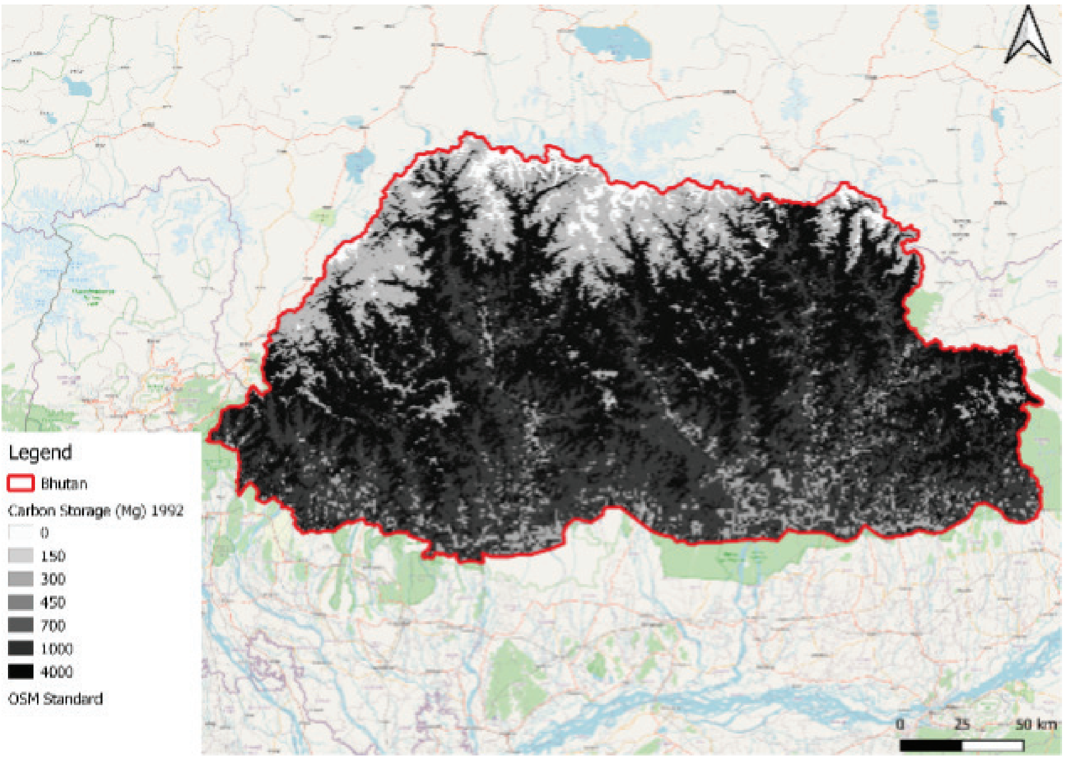
lucode	C_above	C_below	C_soil	C_dead
0	29.61	10.9557	1.36	0
10	29.61	10.9557	1.36	0
11	7.755	2.86935	1.36	0
12	23.5	8.695	1.36	0
20	14.1	5.217	1.36	0
30	14.1	5.217	1.36	0
40	61.1	22.607	1.36	0
50	61.1	22.607	1.36	0
60	282	104.34	1.36	0
61	47	17.39	1.36	0
62	61.1	22.607	1.36	0
70	282	104.34	1.36	0
71	47	17.39	1.36	0
72	61.1	22.607	1.36	0
80	282	104.34	1.36	0
81	47	17.39	1.36	0
82	84.6	31.302	1.36	0
90	61.1	22.607	1.36	0
100	47	17.39	1.36	0
110	18.8	6.956	1.36	0
120	18.8	6.956	1.36	0
121	18.8	6.956	1.36	0

lucode	C_above	C_below	C_soil	C_dead
122	18.8	6.956	1.36	0
130	14.1	5.217	1.36	0
140	23.5	8.695	1.36	0
150	23.5	8.695	1.36	0
151	23.5	8.695	1.36	0
152	23.5	8.695	1.36	0
153	0	0	0	0
160	0	0	0	0
170	0	0	0	0
180	0	0	0	0
190	0	0	0	0
200	0	0	0	0
201	0	0	0	0
202	0	0	0	0
210	0	0	0	0
220	0	0	0	0

C2.2 Results—ESA/CCI-LC Maps

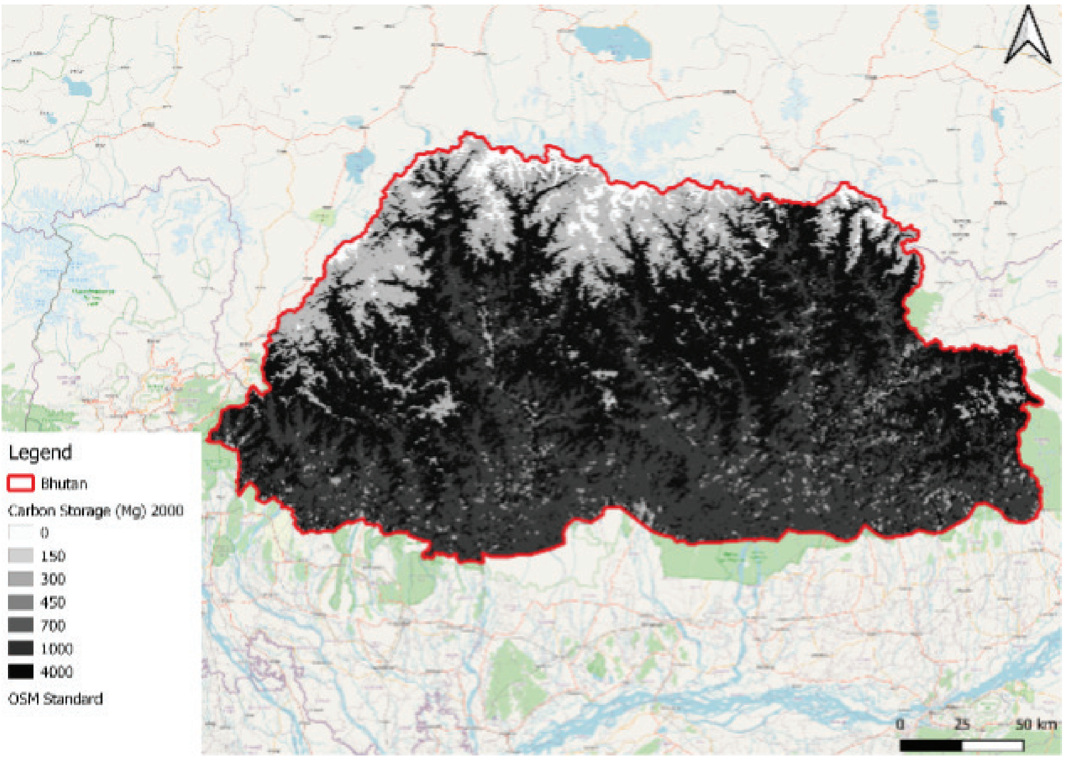
Figures C9, C10, C11, and C12 show the amount (in megagrams) of carbon stored in each pixel in 1992, 2000, 2010, and 2015 respectively. They are a sum of all the carbon pools provided by the biophysical table.

Figure C9. Carbon model output 1992



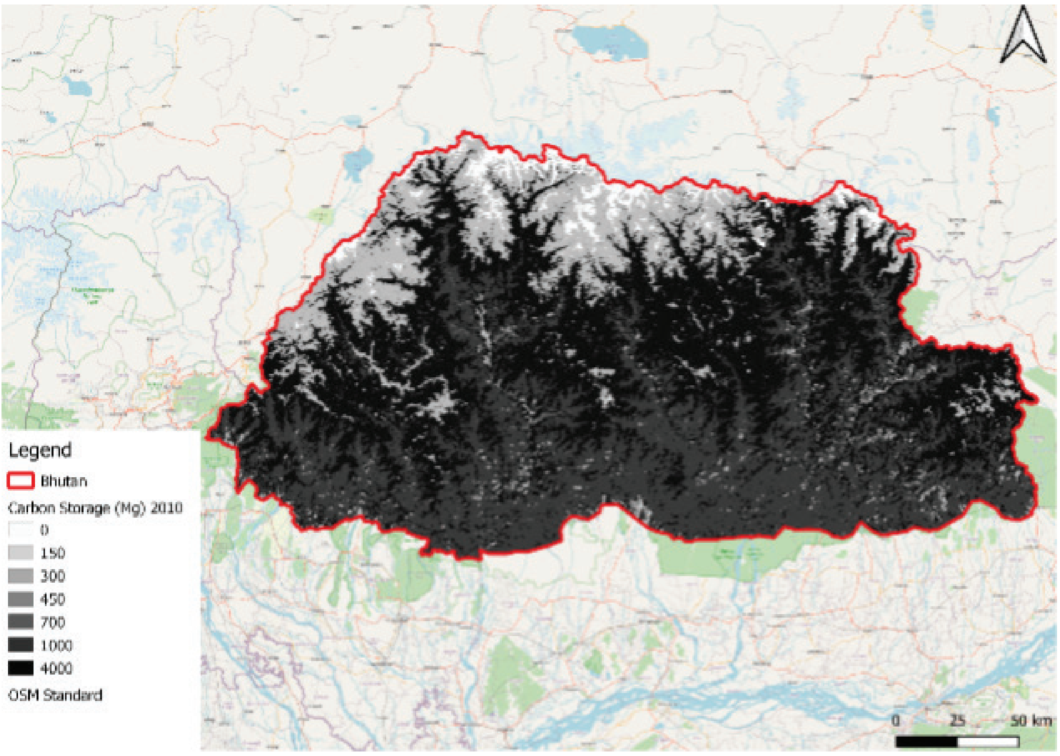
Source: Authors' diagram.

Figure C10. Carbon model output 2000



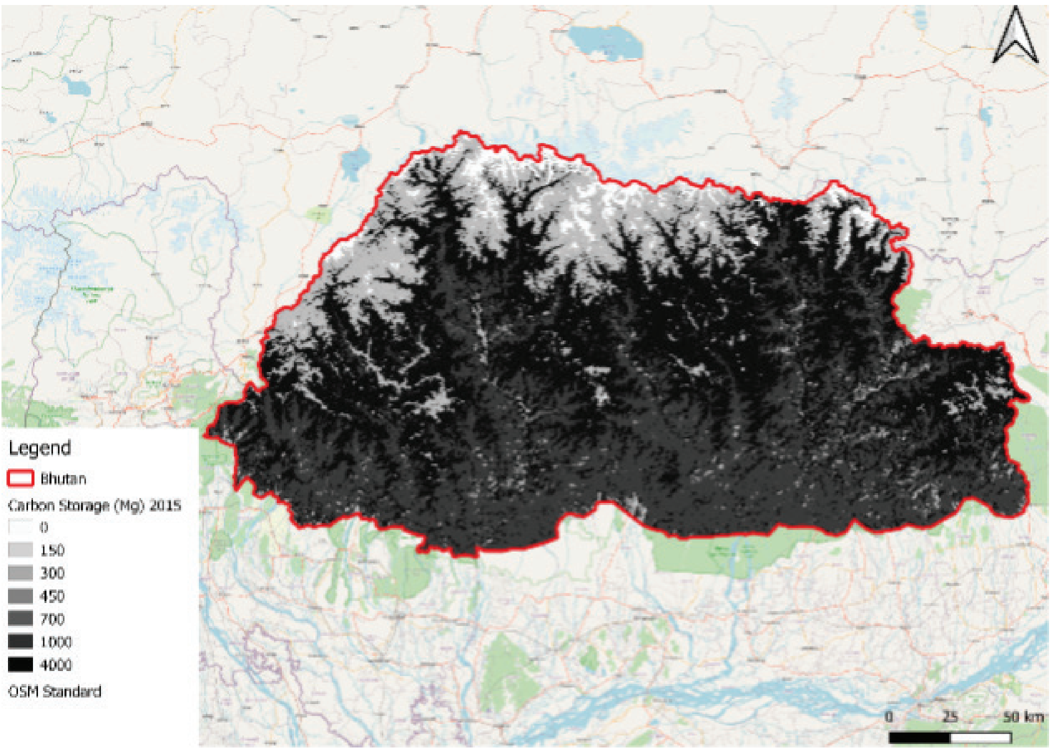
Source: Authors' diagram.

Figure C11. Carbon model output 2010



Source: Authors' diagram.

Figure C12. Carbon model output 2015



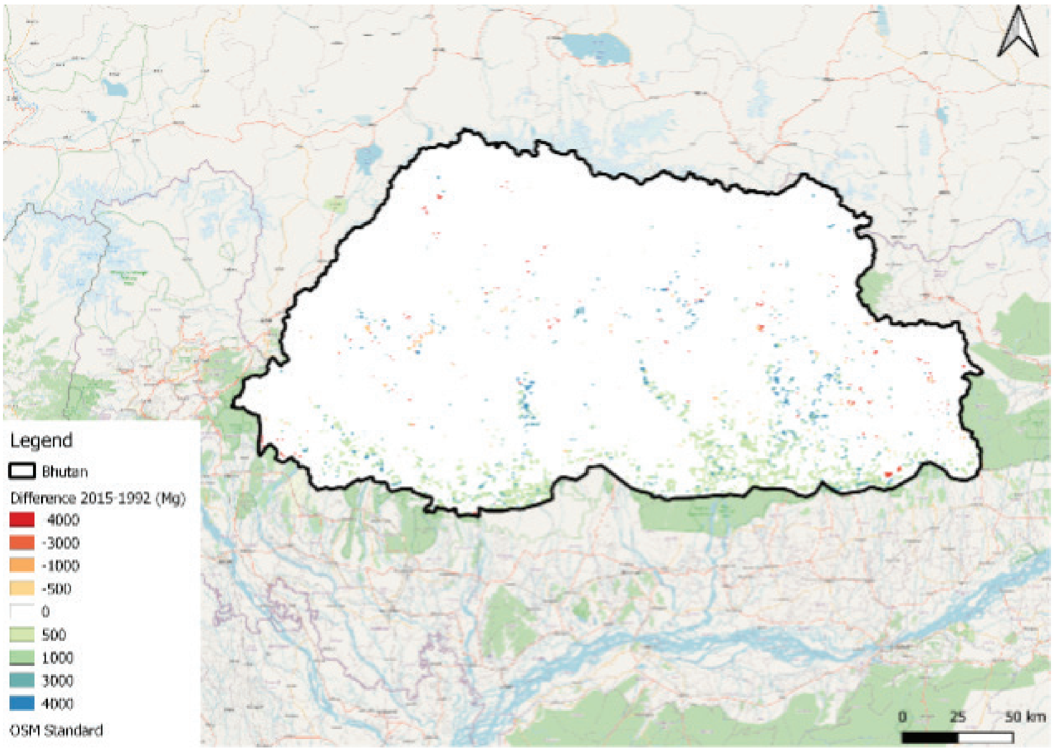
Source: Authors' diagram.

Table C2. Carbon pool statistics

Year	Carbon Stored (Mg)	Change from 1992	Change from 2000
1992	1,004,020,794		
2000	1,019,225,860	1.51%	
2010	1,027,340,515	2.32%	0.80%
2015	1,027,187,676	2.31%	0.78%

As Table C2 shows, the amount of carbon stored in Bhutan has increased by 2.31% from 1992 to 2015. However, the carbon stored in 2010 was higher than that stored in 2015. The results suggest that forestation occurred between 1992 to 2010, while deforestation (although limited) characterized the years between 2010 and 2015. To help visualize where declines in carbon storage occurred, we calculated in QGIS the difference in carbon stored from 1992 to 2015 (Figure C13).

Figure C13. Carbon storage difference (2015–1992)

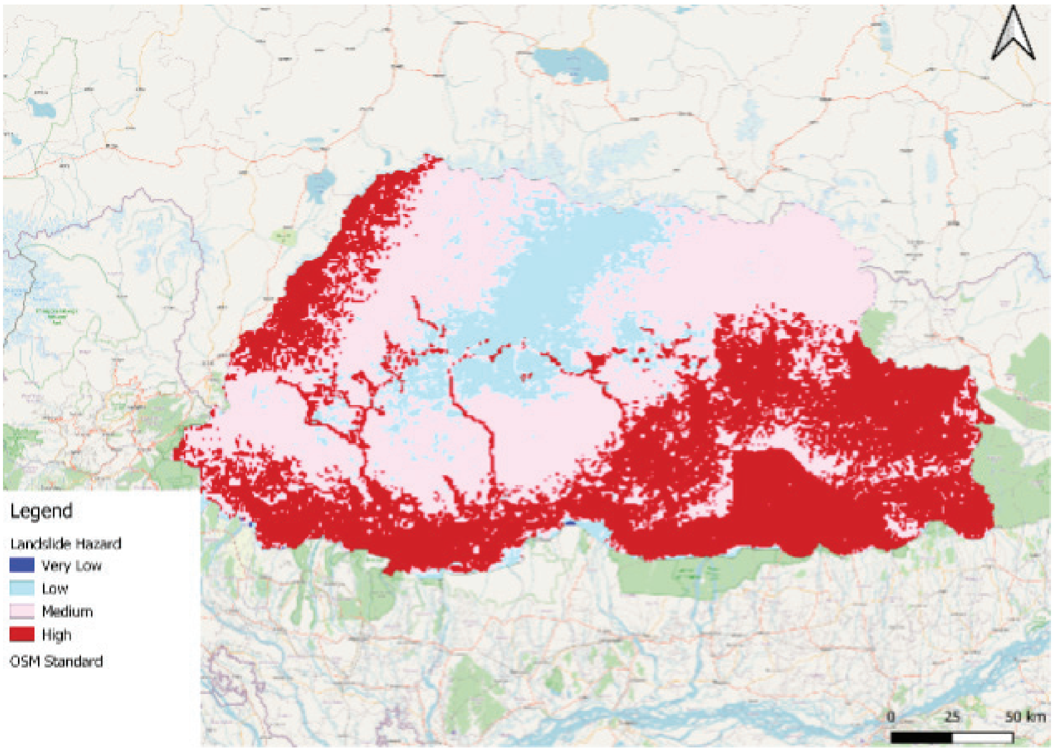


Source: Authors' diagram.

C2.3 Carbon Storage Change and Landslide Hazard

We downloaded the Global Landslide Hazard Map from the Global Facility for Disaster Reduction and Recover website (Amadio, 2020). This project defines landslide hazard as the average annual frequency of occurrence of a significant landslide occurring within a defined area. The landslide hazard has been simplified into four categories, ranging from Very Low to High, as Figure C14 shows.

Figure C14. Landslide hazard in Bhutan



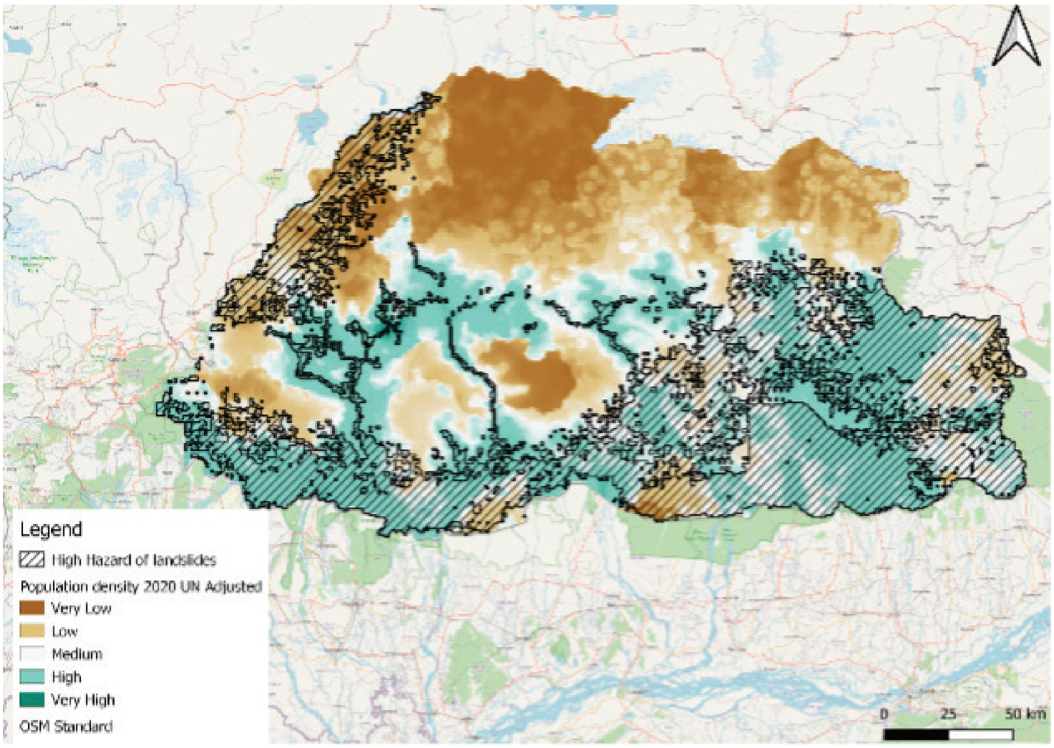
Source: Authors' diagram based on data from Amadio (2020) and OpenStreetMap (© OpenStreetMap contributors, https://www.openstreetmap.org/copyright).

We then considered only the areas in Bhutan that show a "High" hazard of landslides. Using the data shown in Figure C13, which indicates the increases or declines of carbon storage from 1992 to 2015, we calculated the % of pixels with a negative carbon value in the high-hazard areas compared to their total in the whole country. In other words, we calculated the share of pixels where carbon storage has declined from 1992 to 2015 in the areas with a high hazard of landslides, compared to the total number of pixels in Bhutan where carbon stocks have declined. The calculation was done in QGIS 3.10.

Our results indicate that 54% of pixels with a negative value of carbon storage can be found in the areas characterized by a high hazard of landslides, suggesting that deforestation may have occurred in already vulnerable areas. However, we also calculated the share of pixels where carbon storage has increased, and we found that 77% of them are in the regions with a high hazard of landslides. It would be necessary to retrieve landslide hazard maps of Bhutan showing the hazard in 1992 and in 2015 to conclude if and how land-use changes may affect landslides.

From our results, we may be able to conclude that the areas with a high hazard are also the ones where land-use changes have occurred the most, probably because they are also very densely populated compared to the rest of the country, as shown in Figure C15. However, it should be noted that 39% of pixels shown in Figure C14 are classified as "high hazard," while the pixels where land-use changes have occurred from 1992 to 2015 (Figure C13) are just 6% of the total. Therefore, these results are not strong enough to indicate that land-use changes occurred in high-hazard places with high population density. This conclusion may still be true, and further research may be needed to confirm our results. Another possible conclusion is that carbon storage may have increased in landslide-prone areas exactly because of the hazard, but, as written above, further research may be needed to confirm this hypothesis.

Figure C15. Population density map and high hazard of landslides



Source: Authors' diagram based on data from WorldPop and Center for International Earth Science Information Network (CIESIN) (2020) and Amadio (2020).

C2.4 Input Data Preparation and Processing—LULC 2016 Map

LULC maps: See Section C1.4

1. Carbon Pools: Table of LULC classes, containing data on carbon stored in each of the four fundamental pools for each LULC class.
    - Carbon above ground: The values of carbon density in aboveground mass (Mg/ha or tons/ha) of each land-use type are shown in Table C3.

- Carbon below ground: The values of carbon density in belowground mass (Mg/ha) of each land-use type are shown in Table C3.
- Carbon stored in organic matter: The values of carbon density in dead mass (Mg/ha) of each land-use type are shown in Table C3.
- Carbon stored in soil: The values of carbon density in dead mass (Mg/ha) of each land-use type are shown in Table C3.

The unit of measurement for these coefficients is Mg/ha. Average carbon coefficient values have been found in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories report, chapter 4 "Agriculture, Forestry and Other Land Use" (IPCC, 2006).

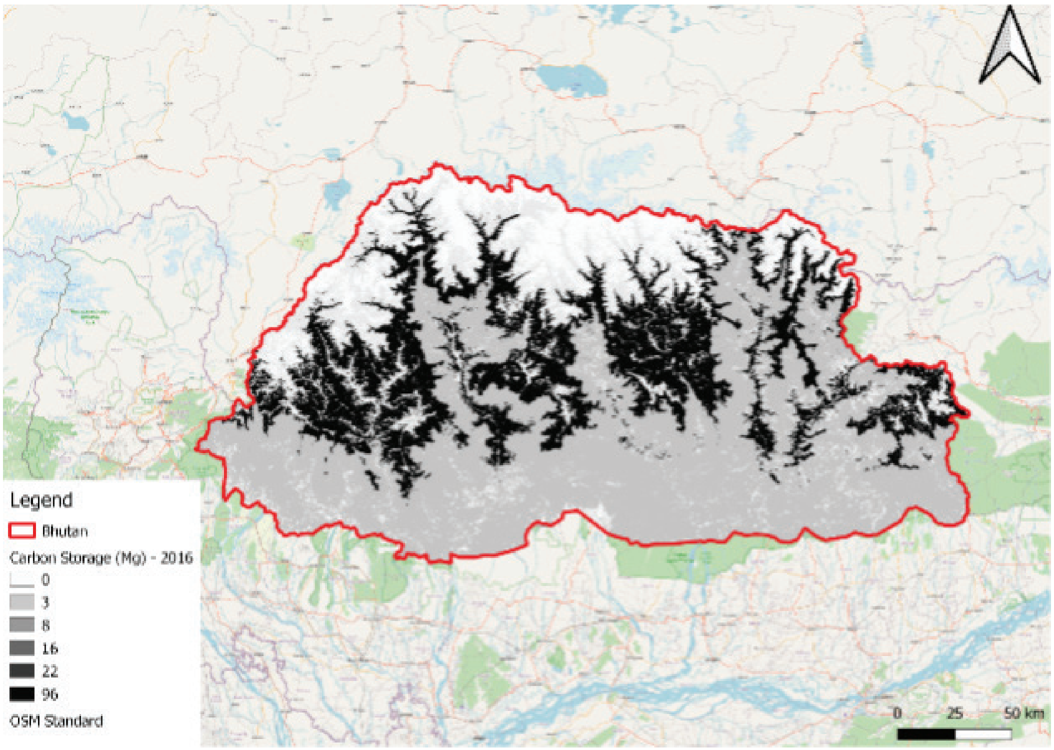
Table C3. Carbon pools LULC 2016

lucode	C_above	C_below	C_soil	C_dead
301	18.8	6.956	1.36	0
302	18.8	6.956	1.36	0
303	0	0	0	0
304	61.1	22.607	1.36	0
305	282	104.34	1.36	0
306	0	0	0	0
307	7.755	2.86935	1.36	0
308	282	104.34	1.36	0
309	0	0	0	0
310	23.5	8.695	1.36	0
311	47	17.39	1.36	0
312	282	104.34	1.36	0
313	18.8	6.956	1.36	0
314	0	0	0	0
315	0	0	0	0
316	0	0	0	0
317	0	0	0	0
318	282	104.34	1.36	0
319	0	0	0	0
320	0	0	0	0

C2.5 Results—LULC 2016 Map

Figure C16 shows the amount (in megagrams) of carbon stored in each pixel in 2016.

Figure C16. Carbon model output 2016



Source: Authors' diagram.

Table C4. Carbon pool statistics

Year	Carbon Stored (Mg)
2016	692,132,498

As Table C4 shows, the amount of carbon stored in Bhutan using the LULC 2016 map indicates that the Mg of C is around 30% smaller than was stored in 2015 using the ESA/CCI-LC map (Table C2). There are different reasons to explain this difference; for example, the carbon pools that we created were not precise enough to be comparable (Table C1 and Table C3), or it is possible that since the different LULC maps have different resolutions (300 m and 50 m) then they have different precision in capturing the land covers.

A reference suggested that Bhutan stored 706 million metric tons in 2018 (Palden, 2018), suggesting that the InVEST results using the LULC 2016 map are more reliable than the ones that used the LULC maps developed by ESA/CCI-LC.

C3 Habitat Quality

C3.1 Input Data Preparation and Processing—ESA/CCI-LC Maps

1. **LULC maps:** See Section C1.4
2. **Threat Data:** Several major threats such as cropland areas, urban areas, and the road network have been identified as threat sources to the natural habitat and biodiversity. See Table C5. See Table C15 for data sources.

Table C5. Table of threat (maximum distance, weighted value, and decay function) for InVEST simulation

THREAT	Description	MAX_DIST	WEIGHT	DECAY
crop_10	Cropland, rainfed	4	0.7	linear
crop_11	Cropland, rainfed (Herbaceous cover)	4	0.7	linear
crop_12	Cropland, rainfed (Tree or shrub cover)	6	0.7	linear
crop_20	Cropland, irrigated or post-flooding	0.5	0.5	Exponential
mosa_30	Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%)	0.5	0.3	linear
urb_190	Urban areas	7.1	0.7	linear

3. **Sensitivity of land cover types to each threat:** Table C6 characterizes each LULC type to be habitat or non-habitat and the type's sensitivity to the threats (see Table C16). The table contains the following fields:

   3.1 LULC: Codes identify each LULC class

   3.2 Name: Abbreviation of each LULC class

   3.3 Habitat: Score characterizing each LULC as habitat or non-habitat. The values of 0 and 1 are used for the purpose, with 0 for non-habitat class and 1 for habitat class of LULC.

   3.4 L_crop_10, L_crop_11, L_crop_12, L_crop_20, mosa_30_c, urb_190_c: These are columns for the relative sensitivity of LULC classes to the threat.

4. **Half-saturation constraint:** The default value of 0.5 was used.

Table C6. Table of sensitivity of land cover types to each threat for InVEST simulation.

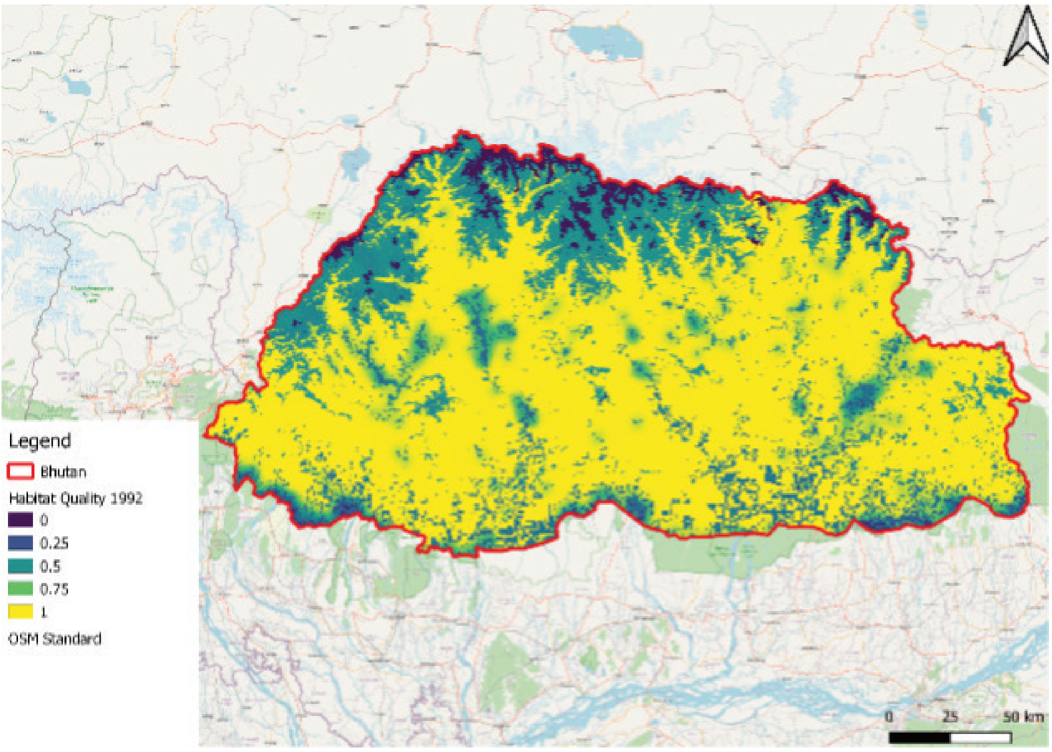
LULC	HABITAT	crop_10	crop_11	crop_12	crop_20	mosa_30	urb_190
0	0	0	0	0	0	0	0
10	0.4	0.03	0.03	0.03	0.03	0.03	0.69
11	0.4	0.03	0.03	0.03	0.03	0.03	0.69
12	0.4	0.03	0.03	0.03	0.03	0.03	0.69
20	0.4	0.03	0.03	0.03	0.03	0.03	0.69
30	0.4	0.03	0.03	0.03	0.03	0.03	0.69
40	0.5	1	1	1	1	1	1
50	1	1	1	1	1	1	1
60	1	1	1	1	1	1	1
61	1	1	1	1	1	1	1
62	1	1	1	1	1	1	1
70	1	1	1	1	1	1	1
71	1	1	1	1	1	1	1
72	1	1	1	1	1	1	1
80	1	1	1	1	1	1	1
81	1	1	1	1	1	1	1
82	1	1	1	1	1	1	1
90	1	1	1	1	1	1	1
100	0.5	1	1	1	1	1	1
110	0.5	1	1	1	1	1	1
120	0.4	1	1	1	1	1	1
121	0.4	1	1	1	1	1	1
122	0.4	1	1	1	1	1	1
130	0.5	1	1	1	1	1	1
140	0.5	0	0	0	0	0	0
150	0.5	1	1	1	1	1	1
151	0.5	1	1	1	1	1	1
152	0.5	1	1	1	1	1	1
153	0.5	1	1	1	1	1	1

LULC	HABITAT	crop_10	crop_11	crop_12	crop_20	mosa_30	urb_190
160	1	1	1	1	1	1	1
170	1	1	1	1	1	1	1
180	0.5	1	1	1	1	1	1
190	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0
201	0	0	0	0	0	0	0
202	0	0	0	0	0	0	0
210	0.3	0.7	0.7	0.7	0.7	0.7	0.8
220	0	0	0	0	0	0	0

C3.2 Results—ESA/CCI-LC Maps

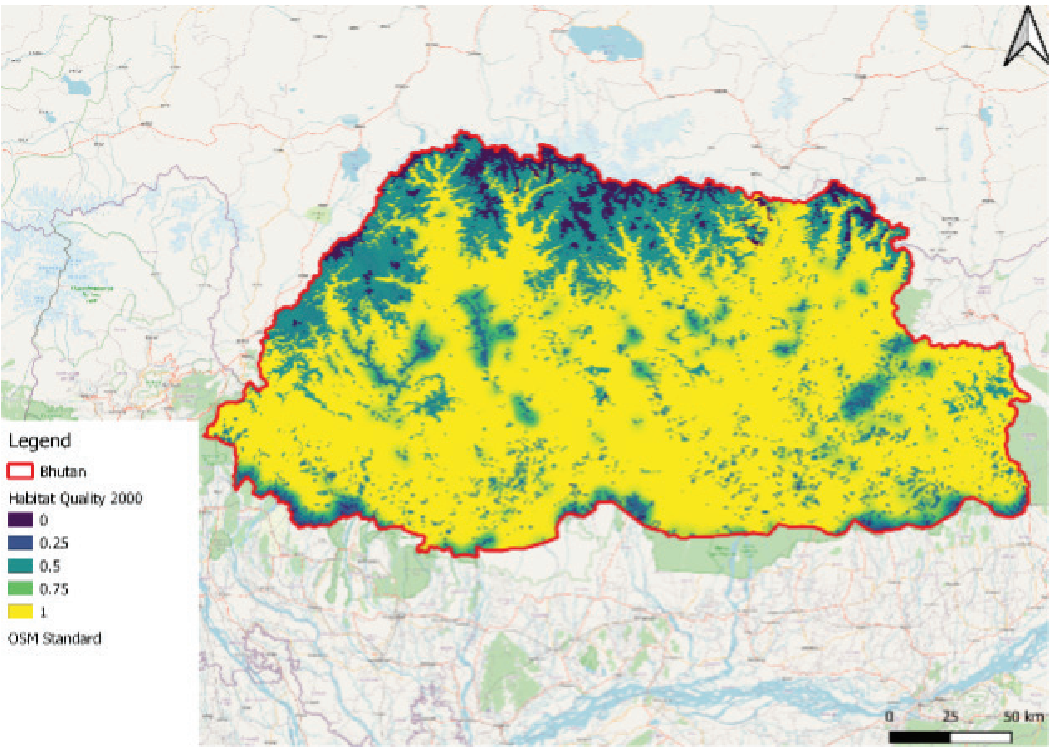
Figures C17, C18, C19, and C20 show the relative level of habitat quality in Bhutan in 1992, 2000, 2010, and 2015 respectively. Higher numbers indicate better habitat quality vis-a-vis the distribution of habitat quality across the rest of the landscape. Areas on the landscape that are not habitat get a quality score of 0. The habitat score values range from 0 to 1, where 1 indicates the highest habitat suitability.

Figure C17. Scores of habitat quality—1992



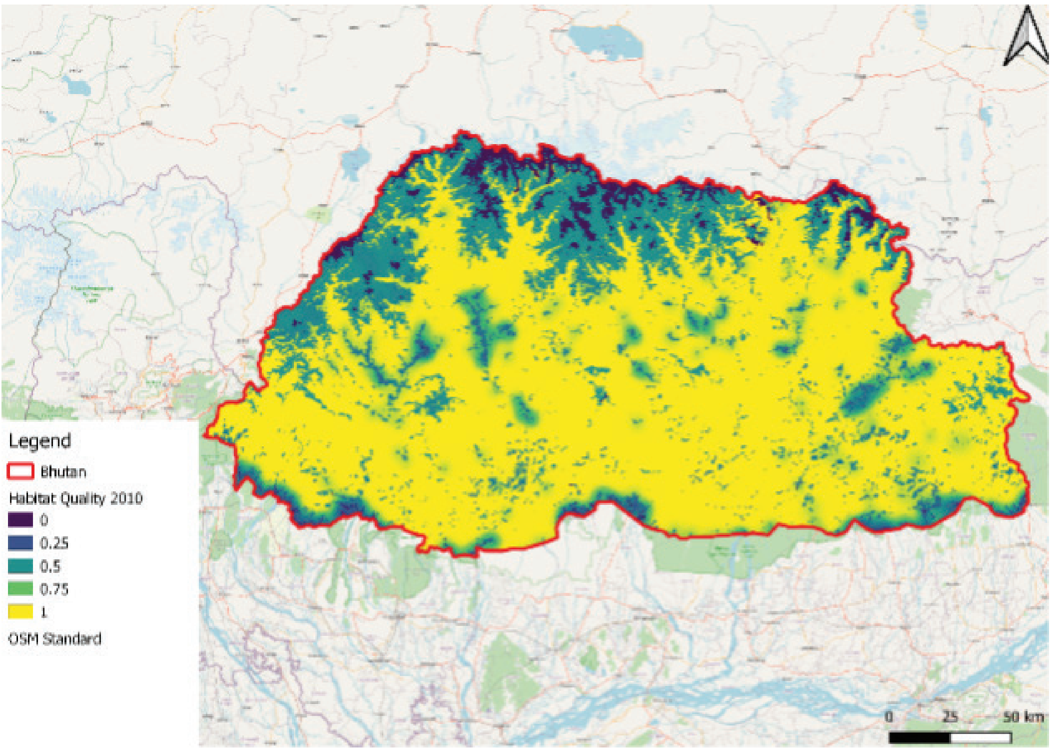
Source: Authors' diagram.

Figure C18. Scores of habitat quality—2000



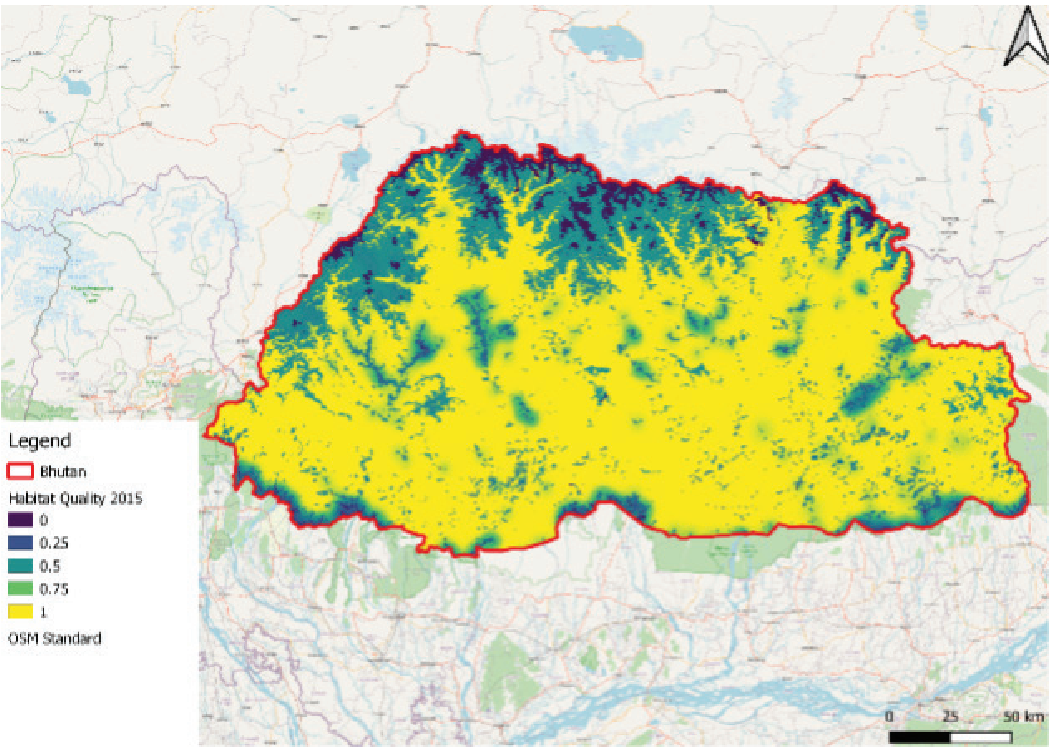
Source: Authors' diagram.

Figure C19. Scores of habitat quality—2010



Source: Authors' diagram.

Figure C20. Scores of habitat quality—2015



Source: Authors' diagram.

Table C7. Habitat quality statistics

Year	Mean of HQ	Change from 1992	Change from 2000
1992	0.814		
2000	0.829	1.90%	
2010	0.833	2.33%	0.42%
2015	0.833	2.33%	0.42%

As Table C7 shows, since 1992 the mean of habitat quality in Bhutan increased by 1.90% and by 2.33% in 2000 and 2010 respectively. However, in 2015 the mean of habitat quality has not changed compared to 2010, indicating that no relevant changes have occurred during those years.

C3.3 Input Data Preparation and Processing—LULC 2016

1. **LULC maps:** See Section 1.4. It should be noted that the areas outside Bhutan still have an impact on habitat quality. This is why we merged the LULC 2016 map with a buffer of areas outside the country using the LULC 2015 ESA/CCI-LC map.
2. **Threat Data:** Several major threats, such as cropland areas, urban areas, and the road network have been identified as the threat sources to the natural habitat and biodiversity. See Table C8. See Table C15 for data sources.

Table C8. Table of threat (maximum distance, weighted value, and decay function) for InVEST simulation

THREAT	Description	MAX_DIST	WEIGHT	DECAY
crop_10	Cropland, rainfed	4	0.7	linear
crop_11	Cropland, rainfed (Herbaceous cover)	4	0.7	linear
crop_12	Cropland, rainfed (Tree or shrub cover)	6	0.7	linear
crop_20	Cropland, irrigated or post-flooding	0.5	0.5	Exponential
mosa_30	Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%)	0.5	0.3	linear
urb_190	Urban areas	7.1	0.7	linear
urb_303	Urban areas	7.1	0.7	linear
crop_307	Dry Land Paddy	4	0.7	linear
crop_310	Wet Land Paddy	0.5	0.5	Exponential

3. **Sensitivity of land cover types to each threat:** Table C6 characterizing each LULC type to be habitat or non-habitat and the type's sensitivity to the threats (see Table C14). The table contains the following fields:

   3.1 LULC: Codes identify each LULC class

   3.2 Name: Abbreviation of each LULC class

   3.3 Habitat: Score characterizing each LULC as habitat or non-habitat. The values of 0 and 1 are used for the purpose, with 0 for non-habitat class and 1 for habitat class of LULC.

   3.4 L_crop_10, L_crop_11, L_crop_12, L_crop_20, mosa_30_c, urb_190_c, urb_303_c, crop_307_c, crop_310_c: These are columns for the relative sensitivity of LULC classes to the threat.

4. **Half-saturation constraint.** The default value of 0.5 was used.

Table C9. Table of sensitivity of land cover types to each threat for InVEST simulation

LULC	HABITAT	crop_10	crop_11	crop_12	crop_20	mosa_30	urb_190	urb_303	crop_307	crop_310
0	0	0	0	0	0	0	0	0	0	0
10	0.4	0.03	0.03	0.03	0.03	0.03	0.69	0.69	0.03	0.03
11	0.4	0.03	0.03	0.03	0.03	0.03	0.69	0.69	0.03	0.03
12	0.4	0.03	0.03	0.03	0.03	0.03	0.69	0.69	0.03	0.03
20	0.4	0.03	0.03	0.03	0.03	0.03	0.69	0.69	0.03	0.03
30	0.4	0.03	0.03	0.03	0.03	0.03	0.69	0.69	0.03	0.03
40	0.5	1	1	1	1	1	1	1	1	1
50	1	1	1	1	1	1	1	1	1	1
60	1	1	1	1	1	1	1	1	1	1
61	1	1	1	1	1	1	1	1	1	1
62	1	1	1	1	1	1	1	1	1	1
70	1	1	1	1	1	1	1	1	1	1
71	1	1	1	1	1	1	1	1	1	1
72	1	1	1	1	1	1	1	1	1	1
80	1	1	1	1	1	1	1	1	1	1
81	1	1	1	1	1	1	1	1	1	1
82	1	1	1	1	1	1	1	1	1	1
90	1	1	1	1	1	1	1	1	1	1
100	0.5	1	1	1	1	1	1	1	1	1

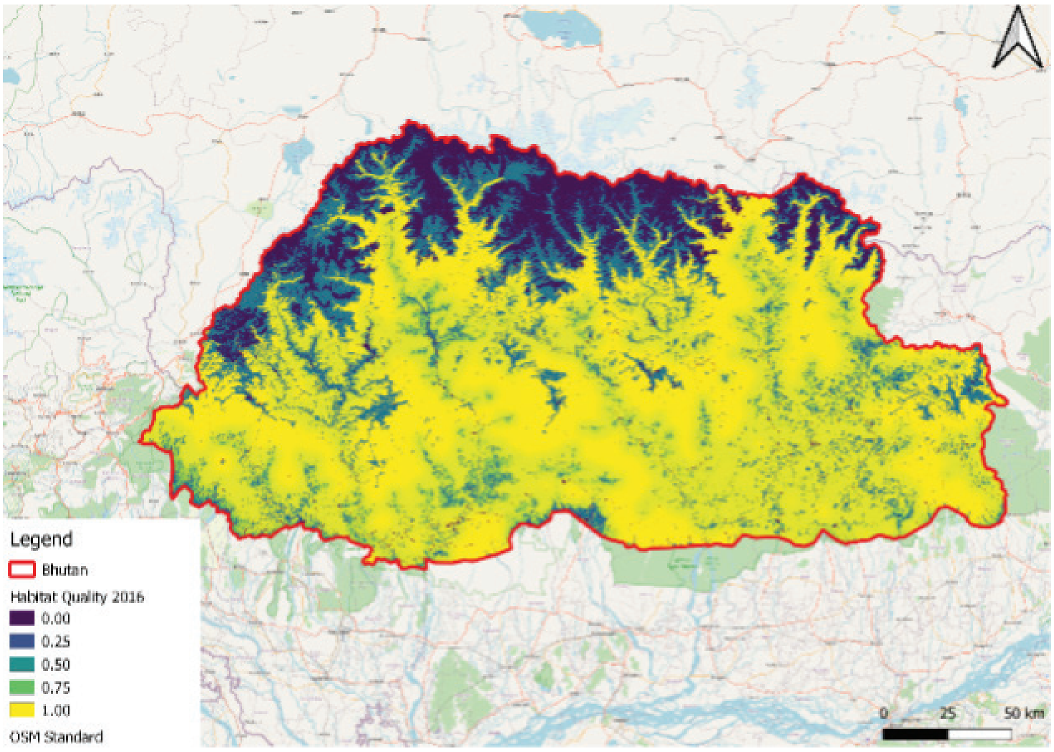
LULC	HABITAT	crop_10	crop_11	crop_12	crop_20	mosa_30	urb_190	urb_303	crop_307	crop_310
110	0.5	1	1	1	1	1	1	1	1	1
120	0.4	1	1	1	1	1	1	1	1	1
121	0.4	1	1	1	1	1	1	1	1	1
122	0.4	1	1	1	1	1	1	1	1	1
130	0.5	1	1	1	1	1	1	1	1	1
140	0.5	0	0	0	0	0	0	0	0	0
150	0.5	1	1	1	1	1	1	1	1	1
151	0.5	1	1	1	1	1	1	1	1	1
152	0.5	1	1	1	1	1	1	1	1	1
153	0.5	1	1	1	1	1	1	1	1	1
160	1	1	1	1	1	1	1	1	1	1
170	1	1	1	1	1	1	1	1	1	1
180	0.5	1	1	1	1	1	1	1	1	1
190	0	0	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0	0	0
201	0	0	0	0	0	0	0	0	0	0
202	0	0	0	0	0	0	0	0	0	0
210	0.3	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.7	0.7
220	0	0	0	0	0	0	0	0	0	0
301	0.4	1	1	1	1	1	1	1	1	1

LULC	HABITAT	crop_10	crop_11	crop_12	crop_20	mosa_30	urb_190	urb_303	crop_307	crop_310
302	0.4	1	1	1	1	1	1	1	1	1
303	0	0	0	0	0	0	0	0	0	0
304	1	1	1	1	1	1	1	1	1	1
305	1	1	1	1	1	1	1	1	1	1
306	0	0	0	0	0	0	0	0	0	0
307	0.4	0.03	0.03	0.03	0.03	0.03	0.69	0.69	0.03	0.03
308	1	1	1	1	1	1	1	1	1	1
309	0.3	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.7	0.7
310	0.4	0.03	0.03	0.03	0.03	0.03	0.69	0.69	0.03	0.03
311	0.5	1	1	1	1	1	1	1	1	1
312	1	1	1	1	1	1	1	1	1	1
313	0.4	1	1	1	1	1	1	1	1	1
314	0	0	0	0	0	0	0	0	0	0
315	0	0	0	0	0	0	0	0	0	0
316	0.3	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.7	0.7
317	0	0	0	0	0	0	0	0	0	0
318	1	1	1	1	1	1	1	1	1	1
319	0	0	0	0	0	0	0	0	0	0
320	0	0	0	0	0	0	0	0	0	0

C3.4 Results—LULC 2016 Map

Figure C21 shows the relative level of habitat quality in Bhutan in 2016. Higher numbers indicate better habitat quality vis-a-vis the distribution of habitat quality across the rest of the landscape. Areas on the landscape that are not habitat get a quality score of 0. The habitat score values range from 0 to 1, where 1 indicates the highest habitat suitability.

Figure C21. Scores of habitat quality—2016



Source: Authors' diagram.

Table C10. Habitat quality statistics

Year	Mean of HQ
2016	0.759

Table C10 shows the mean of habitat quality in 2016 using the LULC 2016 map (and the LULC 2015 ESA/CCI-LC map for the areas outside of Bhutan). As the table indicates, the mean of habitat quality in 2016 is lower than that modelled using only the LULC ESA/CCI-LC maps (Table C7). Since the results of the Carbon model appears to be more reliable using the LULC 2016 map, as described in Section C2.5, it is safe to assume that also these results are closer to reality than the ones obtained using only the LULC ESA/CCI-LC maps.

C4 Urban Flood Risk

C4.1 Input Data Preparation and Processing—ESA/CCI-LC Maps

1. **LULC maps:** See Section C1.4
2. **Depth of rainfall in mm –** for this analysis, we used 162 mm as a reference since this value is indicated by Davies (2021) when a rainfall event was recorded in Bhutan, during a 24-hour period.
3. **Soils Hydrological Group Raster:** Raster of categorical hydrological groups. Pixel values must be limited to 1, 2, 3, or 4, which correspond to soil hydrologic group A, B, C, or D, respectively (used to derive the curve number [CN]). The dataset can be requested from Gijs Simons MSc (https://www.futurewater.eu/our-team/gijs-simons/).
4. **Biophysical Table:** A table containing model information corresponding to each of the land-use classes in the land cover map (Table C11). All LULC classes in the land cover raster must have corresponding values in this table. These values have been derived from sample data provided by InVEST. Each row is a land-use/land cover class, and columns must be named and defined as follows:
    - lucode: LULC class code. LULC codes must match the "value" column in the land cover map raster and must be integer or floating-point values, in consecutive order, and unique.
    - CN values for each LULC type and each hydrologic soil group. Column names should be: CN_A, CN_B, CN_C, CN_D, with the letter suffix corresponding to the hydrologic soil group.

Table C11. Biophysical table

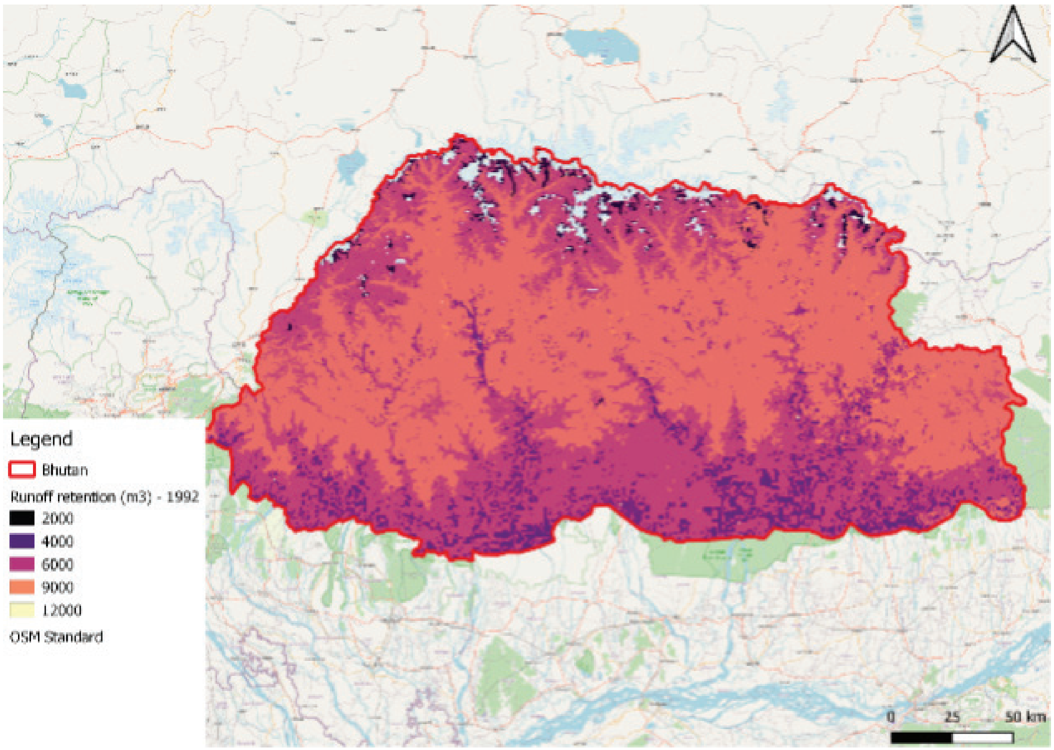
lucode	CN_A	CN_B	CN_C	CN_D
10	64	75	82	85
11	64	75	82	85
12	64	75	82	85
20	64	75	82	85
30	64	75	82	85
40	64	75	82	85
50	36	70	73	79
60	36	70	73	79
61	30	55	70	77
62	45	66	77	83
70	36	70	73	79

lucode	CN_A	CN_B	CN_C	CN_D
71	30	55	70	77
72	45	66	77	83
80	36	70	73	79
81	30	55	70	77
82	45	66	77	83
90	36	70	73	79
100	45	66	77	83
110	45	66	77	83
120	55	72	81	86
121	55	72	81	86
122	55	72	81	86
130	49	69	79	84
140	63	77	85	88
150	63	77	85	88
151	63	77	85	88
152	63	77	85	88
153	63	77	85	88
160	1	1	1	1
170	1	1	1	1
180	1	1	1	1
190	89	92	94	95
200	77	86	91	94
201	77	86	91	94
202	77	86	91	94
210	1	1	1	1
220	77	86	91	94

C4.2 Results—ESA/CCI-LC Maps

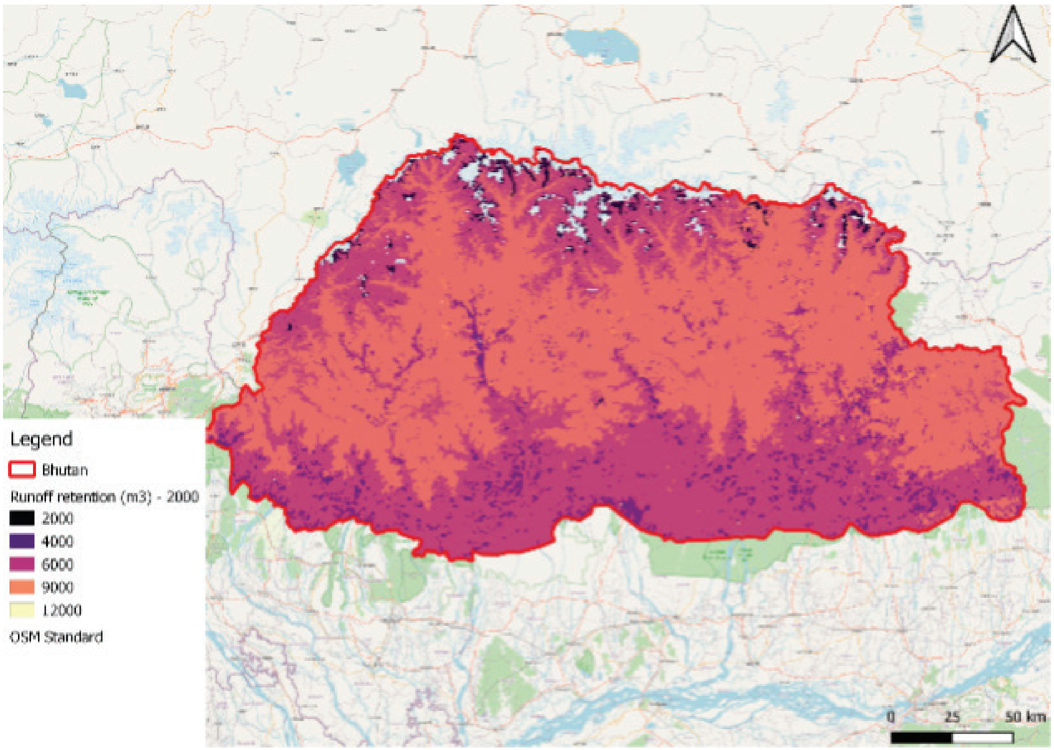
Figures C22, C23, C24, and C25 show the runoff retention volumes (m^3) in the study area in 1992, 2000, 2010, and 2015 respectively.

Figure C22. Runoff retention values (m³)—1992



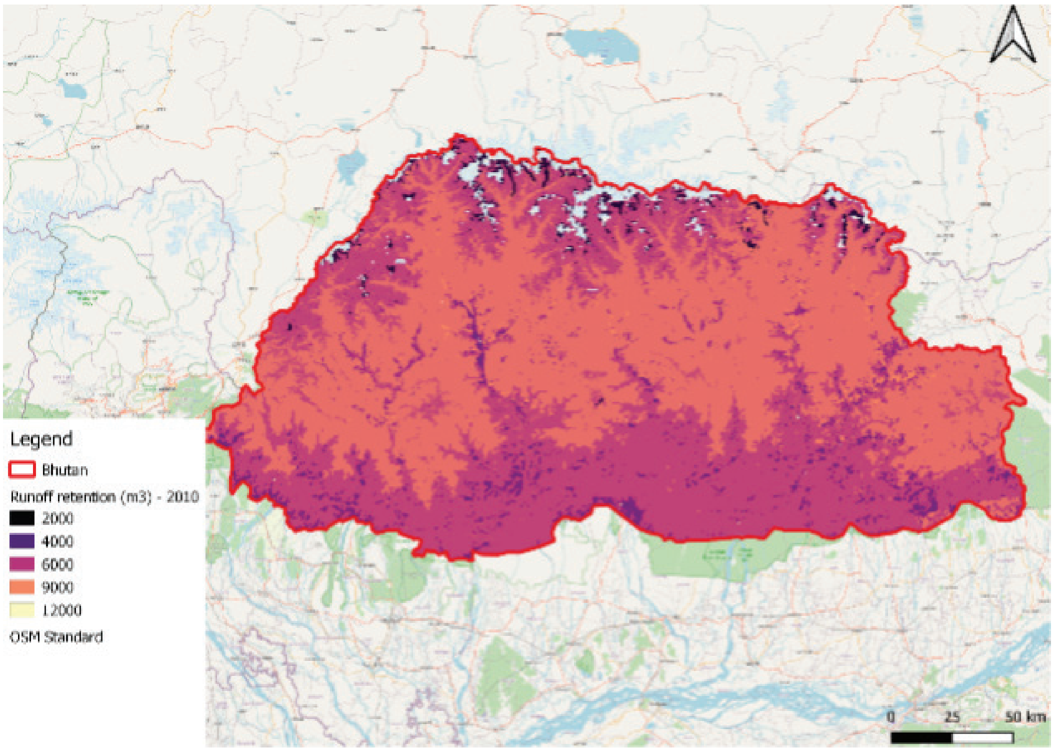
Source: Authors' diagram.

Figure C23. Runoff retention values (m³)—2000



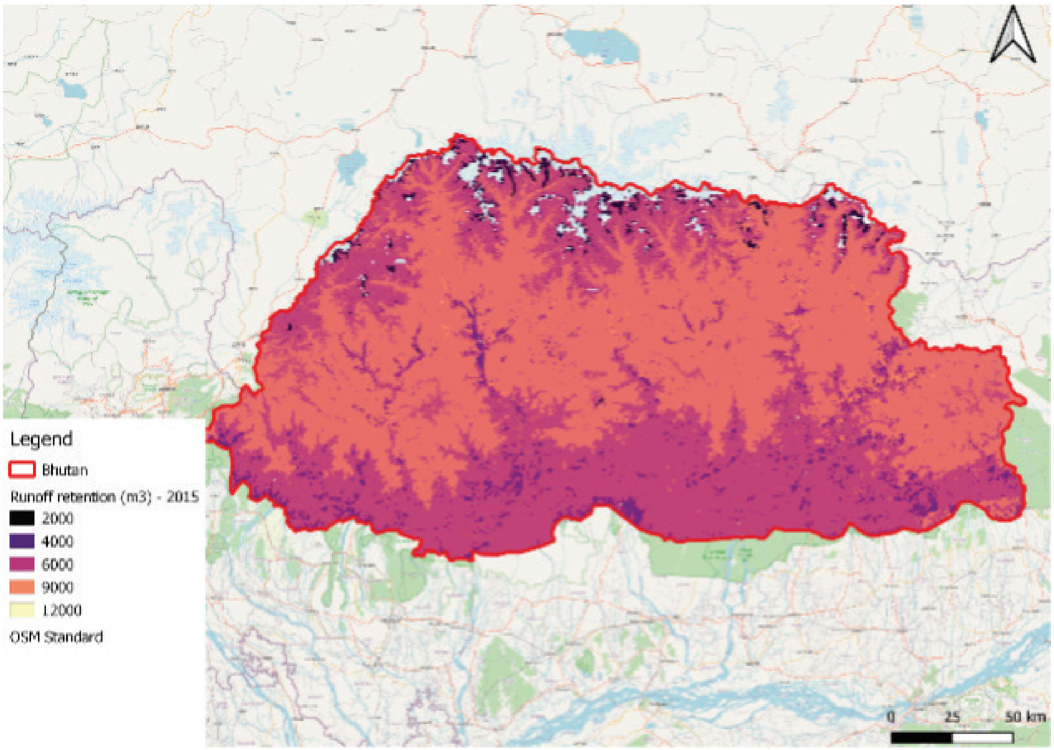
Source: Authors' diagram.

Figure C24. Runoff retention values (m^3)—2010



Source: Authors' diagram.

Figure C25. Runoff retention values (m^3)—2015



Source: Authors' diagram.

Table C12. Runoff retention statistics

Year	Total runoff retention volume (m^3)	Change from 1992	Change from 2000
1992	3,388,366,346		
2000	3,417,362,950	0.9%	
2010	3,428,312,834	1.2%	0.3%
2015	3,428,580,665	1.2%	0.3%

Table C12 shows the total runoff retention volume during a rainfall event of 162 mm in 1992, 2000, 2010, and 2015. The results suggest a trend that is confirmed also by the Carbon Storage and Habitat quality models: from 1992 to 2010 there has been an increase in the forest cover, which in this case led to an increase in the total potential runoff retention volume. However, from 2010 to 2015 the change compared to 1992 remained similar, indicating that no additional relevant land cover changes have occurred in Bhutan.

C4.3 Input Data Preparation and Processing—LULC 2016

1. **LULC maps:** See Section C1.4. It should be noted that some areas outside Bhutan have been considered because watersheds often do not follow political boundaries This is why we merged the LULC 2016 map with a buffer of areas outside the country using the LULC 2015 ESA/CCI-LC map.
2. **Depth of rainfall in mm:** For this analysis, we used 162 mm as a reference since this value is indicated by Davies (2021) when a rainfall event was recorded in Bhutan, during a 24-hour period.
3. **Soils Hydrological Group Raster:** Raster of categorical hydrological groups. Pixel values must be limited to 1, 2, 3, or 4, which correspond to soil hydrologic group A, B, C, or D, respectively (used to derive the CN number). The dataset can be requested from Gijs Simons MSc (https://www.futurewater.eu/our-team/gijs-simons/)
4. **Biophysical Table:** A table containing model information corresponding to each of the land-use classes in the land cover map (Table C13). All LULC classes in the land cover raster must have corresponding values in this table. These values have been derived from sample data provided by InVEST. Each row is a LULC class, and columns must be named and defined as follows:
    - lucode: LULC class code. LULC codes must match the "value" column in the land cover map raster and must be integer or floating-point values, in consecutive order, and unique.
    - CN values for each LULC type and each hydrologic soil group. Column names should be: CN_A, CN_B, CN_C, CN_D, with the letter suffix corresponding to the hydrologic soil group.

Table C13. Biophysical table

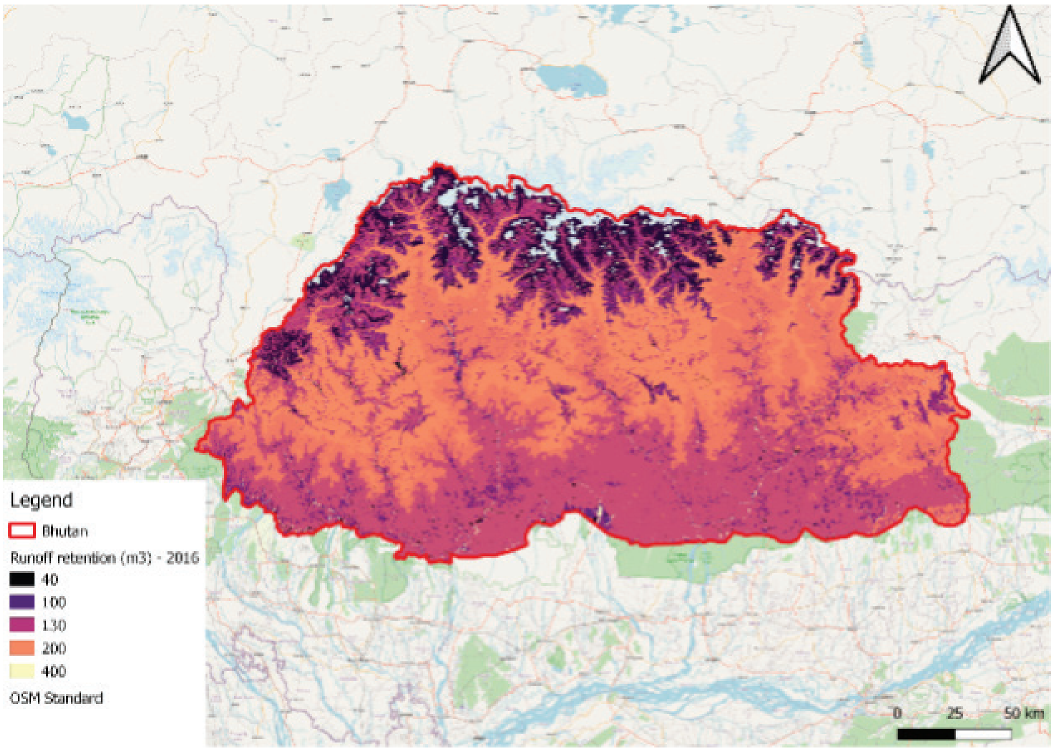
lucode	CN_A	CN_B	CN_C	CN_D
10	64	75	82	85
11	64	75	82	85
12	64	75	82	85
20	64	75	82	85
30	64	75	82	85
40	64	75	82	85
50	36	70	73	79
60	36	70	73	79
61	30	55	70	77
62	45	66	77	83
70	36	70	73	79
71	30	55	70	77
72	45	66	77	83
80	36	70	73	79
81	30	55	70	77
82	45	66	77	83
90	36	70	73	79
100	45	66	77	83
110	45	66	77	83
120	55	72	81	86
121	55	72	81	86
122	55	72	81	86
130	49	69	79	84
140	63	77	85	88
150	63	77	85	88
151	63	77	85	88
152	63	77	85	88
153	63	77	85	88

lucode	CN_A	CN_B	CN_C	CN_D
160	1	1	1	1
170	1	1	1	1
180	1	1	1	1
190	89	92	94	95
200	77	86	91	94
201	77	86	91	94
202	77	86	91	94
210	1	1	1	1
220	77	86	91	94
301	55	72	81	86
302	49	69	79	84
303	89	92	94	95
304	36	70	73	79
305	30	55	70	77
306	77	86	91	94
307	64	75	82	85
308	30	55	70	77
309	1	1	1	1
310	64	75	82	85
311	36	70	73	79
312	30	55	70	77
313	63	77	85	88
314	77	86	91	94
315	77	86	91	94
316	1	1	1	1
317	77	86	91	94
318	36	70	73	79
319	77	86	91	94
320	77	86	91	94

C4.4 Results—ESA/CCI-LC Maps

Figure C26 shows the runoff retention volumes (m³) in the study area in 2016.

Figure C26. Runoff retention values (m³)—2016



Source: Authors' diagram.

Table C14. Runoff retention statistics

Year	Total runoff retention volume (m³)
2016	3,121,956,358

Table C14 shows total runoff retention volume in 2016 using the LULC 2016 map (and the LULC 2015 ESA/CCI-LC map for some areas outside of Bhutan). As the table indicates, the total runoff retention volume in 2016 is lower than that modelled using only the LULC ESA/CCI-LC maps (Table C7). Since the results of the Carbon model appears to be more reliable using the LULC 2016 map, as described in Section C2.5, it is safe to assume that also these results are closer to reality than the ones obtained using only the LULC ESA/CCI-LC maps.

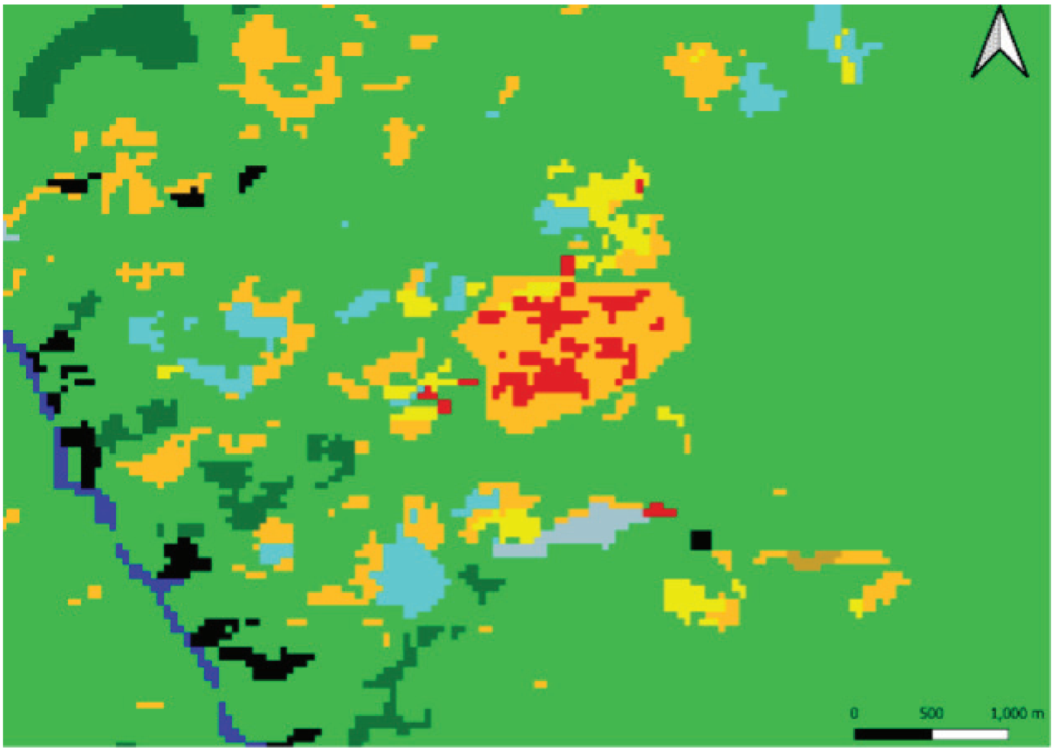
C5 Qualitative Assessment: Focus on a small study area

In this section we considered a village in Bhutan using the map delivered by the Forest Resources and Management Division of the Department of Forests and Park Services (2016) (see Section C1.4). Specifically, we used as spatial inputs in InVEST two land-use scenarios:

- Business-As-Usual (BAU) Scenario: This LULC map is the one delivered by the Ministry of Agriculture and Forests—see Section C1.4—with no additional changes (Figure C27).
- Fruit Trees Scenario: This LULC map is almost identical to one of the BAU scenarios, with the only exception represented by the shrubs found around a village, that have been replaced by fruit trees (Figure C28). Please note that in that figure we coloured the land class "Fruit Trees" in pink.

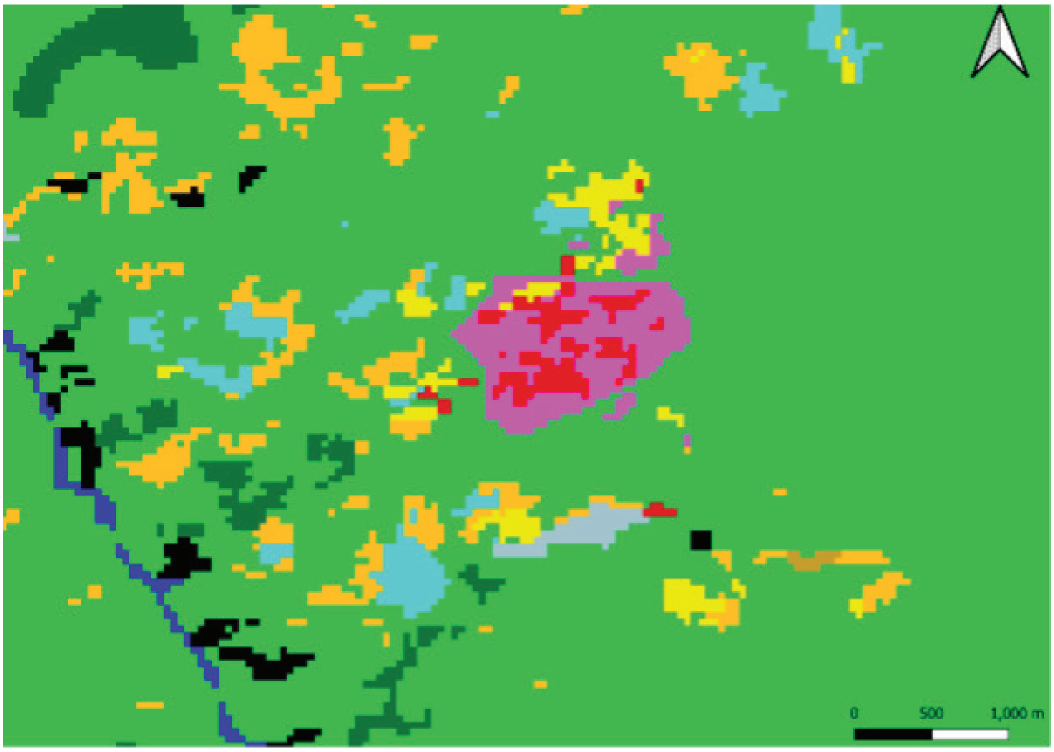
The goal of this qualitative assessment is to show the difference in Carbon Storage, Habitat Quality, and Urban Flood Risk between the two LULC scenarios. Please note that the new land class "Fruit Trees" has been considered as "Orchards," code 311, as shown in Figure C7.

Figure C27. LULC BAU—zoom in on a village in Bhutan.



Source: Authors' diagram based on data from Forest Resources and Management Division of the Department of Forests and Park Services (2016).

Figure C28. LULC fruit trees—zoom in on a village in Bhutan

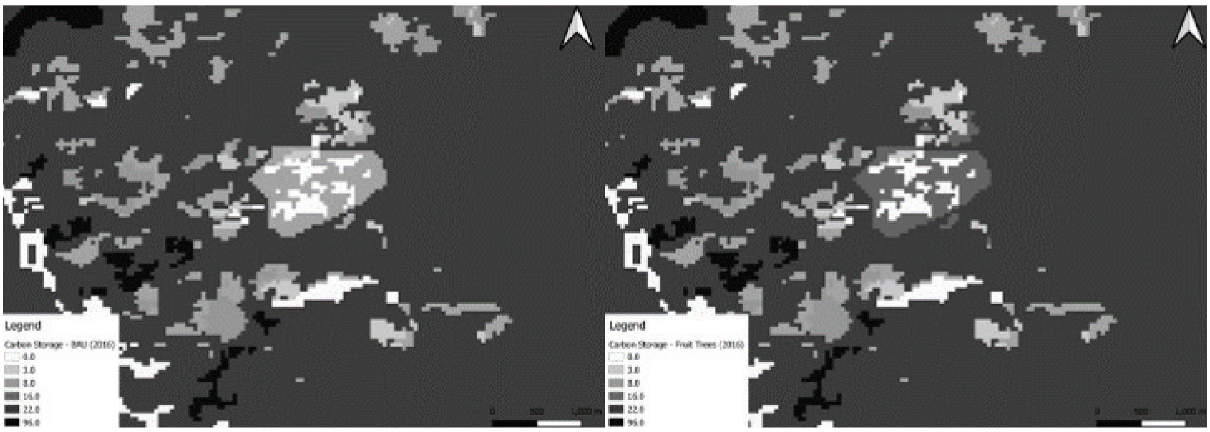


Source: Authors' diagram based on data from Forest Resources and Management Division of the Department of Forests and Park Services (2016).

C5.1 Carbon Storage

Figure C29 illustrates the carbon storage in the BAU and Fruit Trees scenarios. As the figure shows, the area around the village stores around 8 Mg of carbon per pixel (6.7 Mg) and approximately 16.4 Mg of carbon per pixel under the BAU and Fruit Trees scenarios.

Figure C29. Carbon storage in the BAU (left) and Fruit Trees (right) Scenarios

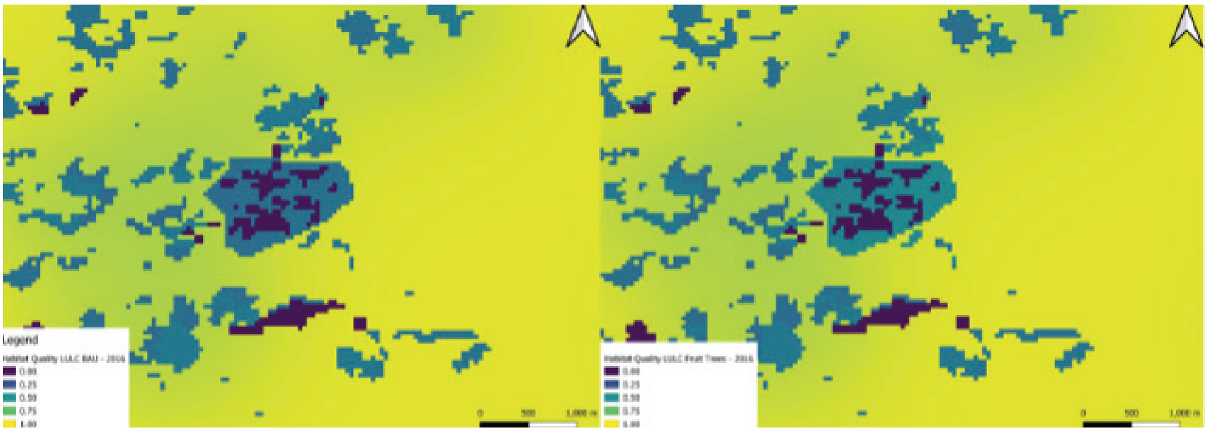


Source: Authors' diagram.

C5.2 Habitat Quality

Figure C30 illustrates the habitat quality in the BAU and Fruit Trees scenarios. As the figure shows, the area around the village is slightly brighter under the Fruit Trees scenario (right), indicating that the habitat quality in the area has increased.

Figure C30. Habitat quality in the BAU (left) and Fruit Trees (right) scenarios

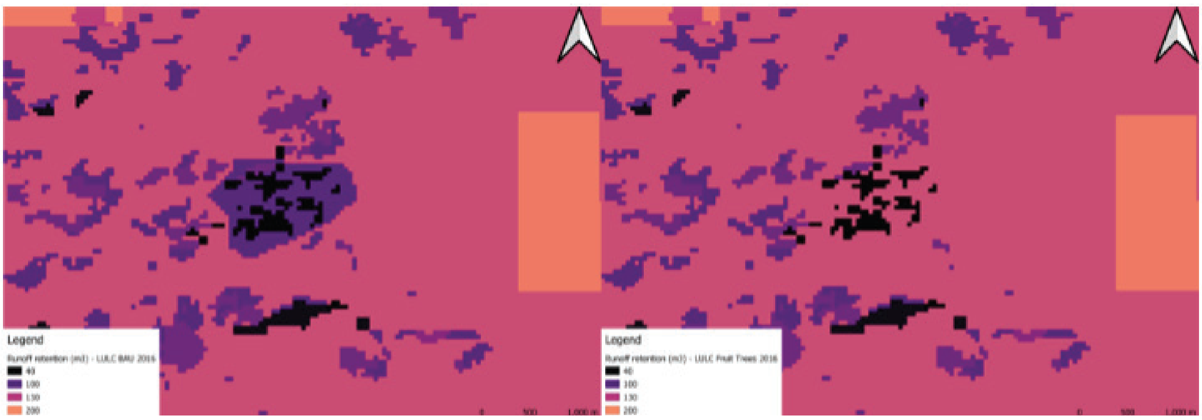


Source: Authors' diagram.

C5.3 Urban Flood Risk

Figure C31 illustrates the runoff retention volumes in the BAU and Fruit Trees scenarios. As the figure shows, the area around the village is characterized by a lower runoff retention volume (100 m^3 per pixel) in the BAU scenario compared to the one in the Fruit Trees scenario (130 m^3 per pixel).

Figure C31. Runoff retention values (m^3) in the BAU (left) and Fruit Trees (right) scenarios



Source: Authors' diagram.

C6 Habitat Quality Appendix

Table C15. Habitat quality model—references "threat table"

Threat	Max_ Distance	Max_ Distance Adopted sources	Weighted value	Weight value adopted sources	Decay function	Decay func. adopted sources
Cropland, rainfed (dry land paddy)	4 km	(Terrado et al., 2016)	0.7	(Bhagabati et al., 2012)	Linear	(Bhagabati et al., 2012)
Cropland, rainfed, herbaceous cover	4 km	(Terrado et al., 2016)	0.7	(Bhagabati et al., 2012)	Linear	(Bhagabati et al., 2012)
Cropland, rainfed (tree or shrub cover)	6 km	(Terrado et al., 2016)	0.7	(Bhagabati et al., 2012)	Linear	(Chu et al., 2018)
Cropland, irrigated or post-flooding (wet land paddy)	0.5 km	(Chu et al., 2018)	0.5	(Chu et al., 2018)	Exponential	(Chu et al., 2018)
Mosaic cropland (>50%)/ natural vegetation (tree, shrub, herbaceous cover) (<50%)	0.5 km	(Ciobotaru et al., 2019)	0.3	(Ciobotaru et al., 2019)	Linear	(Ciobotaru et al., 2019)
Urban areas	7.1 km	(Terrado et al., 2016)	0.7	(Bhagabati et al., 2012)	Linear	(Bhagabati et al., 2012)

Table C16. Habitat quality model—references "threat sensitivity table"

Value	Habitat	Habitat adopted sources	Sensitivity to agricultural source	Sensitivity to agri source adopted sources	Sensitivity to urban areas sources	Sensitivity to urban area adopted sources
10	0.4	(Terrado et al., 2016)	0.03	(Terrado et al., 2016)	0.69	(Terrado et al., 2016)
11	0.4	(Terrado et al., 2016)	0.03	(Terrado et al., 2016)	0.69	(Terrado et al., 2016)
12	0.4	(Terrado et al., 2016)	0.03	(Terrado et al., 2016)	0.69	(Terrado et al., 2016)
20	0.4	(Bhagabati et al., 2012)	0.03	(Bhagabati et al., 2012)	0.69	(Bhagabati et al., 2012)
30	0.4	(Bhagabati et al., 2012)	0.03	(Bhagabati et al., 2012)	0.69	(Bhagabati et al., 2012)
40	0.5	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
50	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
60	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
61	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
62	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
70	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
71	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
72	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
80	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
81	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
82	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)

Value	Habitat	Habitat adopted sources	Sensitivity to agricultural source	Sensitivity to agri source adopted sources	Sensitivity to urban areas sources	Sensitivity to urban area adopted sources
90	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
100	0.5	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
110	0.5	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
120	0.4	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
121	0.4	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
122	0.4	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
130	0.5	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
140	0.5	(Bhagabati et al., 2012)	0	(Bhagabati et al., 2012)	0	(Bhagabati et al., 2012)
150	0.5	(Sulistyawan et al., 2017)	1	(Sulistyawan et al., 2017)	1	(Sulistyawan et al., 2017)
152	0.5	(Sulistyawan et al., 2017)	1	(Sulistyawan et al., 2017)	1	(Sulistyawan et al., 2017)
153	0.5	(Sulistyawan et al., 2017)	1	(Sulistyawan et al., 2017)	1	(Sulistyawan et al., 2017)
160	1	(Sulistyawan et al., 2017)	1	(Sulistyawan et al., 2017)	1	(Sulistyawan et al., 2017)
170	1	(Sulistyawan et al., 2017)	1	(Sulistyawan et al., 2017)	1	(Sulistyawan et al., 2017)
180	0.5	(Sulistyawan et al., 2017)	1	(Sulistyawan et al., 2017)	1	(Sulistyawan et al., 2017)
190	0	(Sulistyawan et al., 2017)	0	(Sulistyawan et al., 2017)	0	(Sulistyawan et al., 2017)
200	0	(Sulistyawan et al., 2017)	0	(Sulistyawan et al., 2017)	0	(Sulistyawan et al., 2017)
202	0	(Sulistyawan et al., 2017)	0	(Sulistyawan et al., 2017)	0	(Sulistyawan et al., 2017)

Value	Habitat	Habitat adopted sources	Sensitivity to agricultural source	Sensitivity to agri source adopted sources	Sensitivity to urban areas sources	Sensitivity to urban area adopted sources
210	0.3	(Sulistyawan et al., 2017)	0.7	(Sulistyawan et al., 2017)	0.8	(Sulistyawan et al., 2017)
220	0	(Sulistyawan et al., 2017)	0	(Sulistyawan et al., 2017)	0	(Sulistyawan et al., 2017)
301	0.4	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
302	0.4	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
303	0	(Sulistyawan et al., 2017)	0	(Sulistyawan et al., 2017)	0	(Sulistyawan et al., 2017)
304	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
305	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
306	0	(Sulistyawan et al., 2017)	0	(Sulistyawan et al., 2017)	0	(Sulistyawan et al., 2017)
307	0.4	(Terrado et al., 2016)	0.03	(Terrado et al., 2016)	0.69	(Terrado et al., 2016)
308	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
309	0.3	(Sulistyawan et al., 2017)	0.7	(Sulistyawan et al., 2017)	0.8	(Sulistyawan et al., 2017)
310	0.4	(Terrado et al., 2016)	0.03	(Terrado et al., 2016)	0.69	(Terrado et al., 2016)
311	0.5	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
312	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
313	0.4	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
314	0	(Sulistyawan et al., 2017)	0	(Sulistyawan et al., 2017)	0	(Sulistyawan et al., 2017)
315	0	(Sulistyawan et al., 2017)	0	(Sulistyawan et al., 2017)	0	(Sulistyawan et al., 2017)

Value	Habitat	Habitat adopted sources	Sensitivity to agricultural source	Sensitivity to agri source adopted sources	Sensitivity to urban areas sources	Sensitivity to urban area adopted sources
316	0.3	(Sulistyawan et al., 2017)	0.7	(Sulistyawan et al., 2017)	0.8	(Sulistyawan et al., 2017)
317	0	(Sulistyawan et al., 2017)	0	(Sulistyawan et al., 2017)	0	(Sulistyawan et al., 2017)
318	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)	1	(Bhagabati et al., 2012)
319	0	(Sulistyawan et al., 2017)	0	(Sulistyawan et al., 2017)	0	(Sulistyawan et al., 2017)
320	0	(Sulistyawan et al., 2017)	0	(Sulistyawan et al., 2017)	0	(Sulistyawan et al., 2017)

Appendix D. Other Results Tables

Table D1. Inflated and discounted values for all indicators quantified

	Subtropical plantations	Temperate plantations	Fences	Fences with subtropical plantations	Fences with temperate plantations	Habitat restoration
PRESENT VALUE of COSTS (USD)						
Capital cost	6,769	9,166	3,000	9,769	12,166	9,637
Annual maintenance cost	8,253	5,200	4,420	12,673	9,620	20,327
Total monetary costs	15,023	14,366	7,420	22,442	21,786	29,963
Government opportunity cost	9,587	12,981	4,249	13,836	17,230	13,648
Total costs	24,610	27,348	11,668	36,278	39,016	43,612
PRESENT VALUE of BENEFITS (USD)						
Household income	209,805	318,343	9,967	219,762	328,301	288
Future timber value	1,257	923	0	1,257	923	0
Total benefits	211,062	319,266	9,967	221,019	329,225	288
FINANCIAL INDICATORS						
NPV without opportunity cost (USD)	196,039	304,900	2,548	198,576	307,439	-29,676
NPV with opportunity cost (USD)	186,452	291,918	-1,701	184,740	290,209	-43,324
IRR without opportunity cost	45.8%	43.5%	25.2%	44.9%	42.9%	N/A*
IRR with opportunity cost	37.3%	35.6%	2.0%	34.3%	33.6%	N/A*

* N/A indicates that these IRR values are negative and cannot be calculated by Excel.

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