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Assessing impacts of land-use and land-cover changes

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Assessing impacts of land-use and land-cover changes

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Assessing impacts of land-use and land-cover changes

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Chansopheaktra Sovann

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Abstract:

Tropical forests are essential for global biodiversity, carbon storage, and hydrological regulation, yet accelerating land-use and land-cover change are rapidly eroding these functions across Southeast Asia. In Cambodia, forest conversion surrounding protected landscapes has intensified over recent decades, but its long-term ecological and economic consequences remain poorly quantified because few studies directly link field-based measurements of forest biodiversity with long-term land-cover change, ecosystem-service responses, and carbon value. This thesis aims to assess how land-cover change alters tropical forest biodiversity, ecosystem-service supply, and the economic value of forest carbon by integrating field measurements with satellite-based analysis in Cambodia's protected forests. It combines field observations of forest structure, species diversity, functional traits, and soil condition with machine-learning-based land-cover mapping, time-series mapping of land-cover changes (1991–2021), hydrological modelling, and carbon stock and valuation frameworks relevant to forest carbon accounting. This integration allows consistent assessment of ecosystem changes across spatial and temporal scales. The results show that conversion from intact evergreen forest to regrowth forest and cashew plantations leads to persistent simplification of stand structure, reductions in species and functional trait diversity, and substantial reductions in aboveground biomass. These ecological changes lead to long-term declines in carbon storage and hydrological regulation, which are not compensated by forest regrowth over several decades. Regrowth forests exhibit intermediate conditions, whereas plantation systems provide only limited ecosystem services. When expressed in economic values, land-cover change results in lower biomass and carbon stocks in forests, reduces the opportunities for climate finance, and diminishes potential long-term revenues for both communities and governments. Overall, this thesis shows that land cover provides a central framework through which land-use decisions shape ecosystem functioning and what consequences this has for policy and management decisions, highlighting the critical importance of protecting intact forest.

Key words: tropical forest; ecosystem services; biodiversity; land-use and land-cover change; Cambodia; Southeast Asia

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MADE IN SWEDEN

To my beloved family

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# Abstract

Tropical forests are essential for global biodiversity, carbon storage, and hydrological regulation, yet accelerating land-use and land-cover changes are rapidly eroding these functions across Southeast Asia. In Cambodia, forest conversion surrounding protected landscapes has intensified over recent decades, but its long-term ecological and economic consequences remain poorly quantified because few studies directly link field-based measurements of forest biodiversity with long-term land-cover change, ecosystem-service responses, and carbon value.

This thesis aims to assess how land-cover change alters tropical forest biodiversity, ecosystem-service supply, and the economic value of forest carbon by integrating field measurements with satellite-based analysis in Cambodia's protected forests. It combines field observations of forest stand structure, species diversity, functional traits, and soil condition with machine-learning-based land-cover mapping, time-series mapping of land-cover changes (1991–2021), hydrological modelling, and carbon stock and valuation frameworks relevant to forest carbon accounting. This integration allows consistent assessment of ecosystem changes across spatial and temporal scales.

The results show that conversion from intact evergreen forest to regrowth forest and cashew plantations leads to persistent simplification of stand structure, reduction in species and functional trait diversity, and substantial reductions in aboveground biomass. These ecological changes lead to long-term declines in carbon storage and hydrological regulation, which are not compensated by forest regrowth over several decades. Regrowth forests exhibit intermediate conditions, whereas plantation systems provide only limited ecosystem services. When expressed in economic values, land-cover change results in lower biomass and carbon stocks in forests, reduces the opportunities for climate finances, and diminishes potential long-term revenues for both communities and governments.

Overall, this thesis shows that land cover provides a central framework through which land-use decisions shape ecosystem functioning and what consequences this has for policy and management decisions, highlighting the critical importance of protecting intact tropical forests.

Popular summary

Tropical forests are among the most valuable ecosystems on Earth, sustaining biodiversity, regulating climate, and maintaining water resources that underpin human well-being under the pressure of global population growth and climate change. However, rapid agricultural expansion, infrastructure development, and urbanization are transforming forest landscapes across Southeast Asia. In Cambodia, forest conversion around protected areas has intensified over recent decades, raising concerns about whether the degraded and regrowth forests can maintain the ecological functions and benefits provided by intact forests. Understanding how different forest conditions created by land-cover change affect ecosystem functioning, ecosystem-service supply, and economic value therefore remains a critical scientific and policy challenge.

This thesis aims to assess how land-cover change alters tropical forest biodiversity, ecosystem services, and the economic value of forest carbon by integrating field-based ecological measurements with satellite-based analyses of Cambodia's protected forests. It combines detailed field observations of forest structure, species diversity, functional traits, and soil conditions with machine-learning land-cover mapping, time-series analysis spanning 1991–2021, hydrological modelling, and carbon stock and valuation frameworks relevant to REDD+. This integrated approach enables consistent assessment of ecosystem change across spatial and temporal scales.

The results show that conversion from intact evergreen forests to regrowth forests or cashew plantations leads to systematic ecological degradation. Species diversity, functional trait diversity, stand structure, aboveground biomass, and soil conditions all decline along this land-cover gradient, with intact evergreen forests consistently supporting the highest ecological integrity. These patterns are expressed at the landscape scale, where three decades of forest loss, limited regrowth recovery, and rapid expansion of cashew plantations have reorganized the landscape in the region of the Kulen National Park in Cambodia into a mosaic in which biodiversity and ecosystem functions are increasingly concentrated within the remaining intact forest areas of the protected national park.

These ecological degradations directly translate into weakened ecosystem-service provisions in the landscape. Carbon storage has declined as forest loss and degradation have exceeded gains from regrowth, resulting in persistent reductions in forest carbon stocks. Hydrological regulation has also weakened, with reduced capacity to regulate dry seasonal water availability. Regrowth forests and plantation systems fail to compensate for these losses over decadal timescales, highlighting the irreplaceable role of intact evergreen forests in sustaining carbon storage and water regulation.

When expressed in economic terms, these biophysical changes have substantial societal implications. Declining forest biomass and carbon stocks reduce opportunities for climate finance and long-term revenues for communities and governments, while intact forests represent high-value natural capital for climate change mitigation and ecosystem-service provision. The findings demonstrate that delayed conservation results not only in ecological degradation but also in lost economic opportunities.

Overall, this thesis demonstrates that forest condition, rather than forest extent alone, governs ecosystem functioning and long-term ecosystem-service provision, making land cover a decisive framework through which land-use decisions shape biodiversity, carbon storage, water regulation, and economic value. Protecting intact tropical forests is therefore the most effective strategy for sustaining ecological integrity and long-term benefits for society and should be prioritized over short-term land-use gains in conservation and land-management policies.

Populärvetenskaplig sammanfattning

Tropiska skogar är yttest värdefulla då de upprätthåller biologisk mångfald, reglerar klimatet och säkrar vattenresurser som är grundläggande för människans välbefinnande, särskilt i en tid av global befolkningstillväxt och klimatförändringar. I Sydostasien omvandlas dock skogslandskap snabbt genom jordbruksexpansion, infrastrukturutveckling och urbanisering. I Kambodja har saverkningen av naturskog intensifierats under de senaste decennierna, vilket väcker frågor om huruvida degraderade och återväxande skogar kan upprätthålla de ekologiska funktioner och nyttor som intakta skogar tillhandahåller. Att förstå hur olika skogstillstånd, skapade av markanvändningsförändringar, påverkar ekosystemfunktioner, ekosystemtjänster och deras ekonomiska värde utgör därför en central vetenskaplig och politisk utmaning.

Denna avhandling syftar till att bedöma hur markanvändningsförändringar påverkar tropisk skogsbiodiversitet, ekosystemtjänster och det ekonomiska värdet av skogens kol genom att integrera fältbaserade ekologiska mätningar med satellitbaserade analyser i Kambodjas skyddade skogar. Avhandlingen kombinerar detaljerade fältobservationer av skogsstruktur, artdiversitet, funktionella egenskaper och markförhållanden med maskininlärningsbaserad markklassificering, tidsserieanalys som sträcker sig från 1991 till 2021, hydrologisk modellering samt ett ramverk för uppskattning och värdering av kolförråd relevanta för REDD+. Detta integrerade angreppssätt möjliggör en konsekvent bedömning av ekosystemförändringar över både rumsliga och tidsmässiga skalor.

Resultaten visar att markanvändningsförändringar från intakta skogar till återväxande skogar eller cashewplantager leder till systematisk ekologisk försämring. Artdiversitet, funktionell diversitet, skogsstruktur, biomassa och markförhållanden minskar längs denna markanvändningsgradient, där intakta skogar konsekvent uppvisar högst ekologisk integritet. Dessa mönster framträder även på landskapsnivå, där tre decennier av skogsförlust, begränsad återhämtning och snabb expansion av cashewplantager har omformat landskapet runt Kulens national park i Kambodja till en mosaik där biologisk mångfald och ekosystemfunktioner i allt högre grad koncentreras till kvarvarande intakta skogsområden inom nationalparken.

Denna ekologiska försämring resulterar direkt i en försvagning av ekosystemtjänster på landskapsnivå. Kolförråden har minskat i takt med att skogsförlust och degradering överstigit vinster från återväxt, vilket resulterar i långvariga minskningar av skogens kolinnehåll. Även den hydrologiska regleringen har försvagats, med minskad förmåga att reglera vattentillgången under torrperioden. Återväxande skogar och plantagesystem förmår inte kompensera för dessa förluster, vilket understryker den oersättliga roll som intakta skogar spelar för att upprätthålla kolförråd och vattenreglering.

När dessa biofysiska förändringar uttrycks i ekonomiska termer får de betydande samhälleliga konsekvenser. Minskad skogsbiomassa och lägre kolförråd begränsar möjligheterna till klimatfinansiering och långsiktiga intäkter för både lokalsamhällen och statliga aktörer. Intakta skogar representerar ett högt värderat naturkapital för tillhandahållande av ekosystemtjänster, samt ökar landskapets förmåga att motverka klimatförändringar. Ett fördröjt naturskydd leder inte bara till ekologisk försämring, utan även till förlorade ekonomiska möjligheter.

Sammanfattningsvis visar denna avhandling att skogarnas tillstånd, snarare än deras areella utbredning i sig, är avgörande för ekosystemfunktioner och långsiktig tillhandahållande av ekosystemtjänster. Markanvändning utgör därmed ett centralt ramverk genom vilket beslut om markutnyttjande formar biologisk mångfald, kolförråd, vattenreglering och ekonomiska värden. Att skydda intakta tropiska skogar är därför den mest effektiva strategin för att säkra ekologisk integritet och långsiktiga samhällsnyttor och bör prioriteras framför kortsiktiga markanvändningsvinster i naturvårds- och markförvaltningspolitik.

សេចក្តីសង្ខេបសម្រាប់សាធារណជន

ព្រៃឈើតំបន់ត្រូពិច គឺជាប្រព័ន្ធអេកូឡូស៊ីដ៏មានសារៈសំខាន់បំផុតមួយនៅលើភពផែនដី ដោយវាមានតួនាទីក្នុងការរក្សាទុកជីវចម្រុះ និយ័តកម្មអាកាសធាតុ និងថែរក្សាលំនឹងធនធានទឹក ដែលជាមូលដ្ឋានសម្រាប់សុខុមាលភាពរបស់មនុស្សជាតិ ជាពិសេសក្រោមសម្ពាធនៃការកើនឡើងចំនួនប្រជាជននៅលើសកលលោក និងការប្រែប្រួលអាកាសធាតុ។ យ៉ាងណាមិញ ការពង្រីកវិស័យកសិកម្ម ការអភិវឌ្ឍហេដ្ឋារចនាសម្ព័ន្ធ និងនគរូបនីយកម្ម កំពុងផ្លាស់ប្តូរតំបន់ទេសភាពព្រៃឈើនៅទូទាំងតំបន់អាស៊ីអាគ្នេយ៍យ៉ាងឆាប់រហ័ស។ នៅប្រទេសកម្ពុជា ការបម្លែងព្រៃឈើនៅជុំវិញតំបន់ការពារធម្មជាតិបានកើនឡើងយ៉ាងឆាប់រហ័សក្នុងប៉ុន្មានទសវត្សរ៍ចុងក្រោយនេះ ដែលបង្កើនការព្រួយបារម្ភ ថាតើសមត្ថភាពរបស់ព្រៃឈើដែលបានរិចរិល និងព្រៃដុះឡើងវិញទាំងនោះ អាចថែរក្សាបាននូវមុខងារអេកូឡូស៊ី និងអត្ថប្រយោជន៍ដូចអ្វីដែលព្រៃចាស់(intact forest)ធ្លាប់បានផ្តល់ឱ្យយើងឬទេ។ ដូច្នេះ ការយល់ដឹងអំពីភាពខុសៗគ្នានៃស្ថានភាពព្រៃឈើ ដែលបណ្តាលមកពីការផ្លាស់ប្តូរនៃការប្រើប្រាស់ដី ដែលមានឥទ្ធិពលទៅលើមុខងារប្រព័ន្ធអេកូឡូស៊ី(ecosystem functioning) ការផ្គត់ផ្គង់នូវសេវាកម្មប្រព័ន្ធអេកូឡូស៊ី(ecosystem-service supply) រួមទាំងតម្លៃសេដ្ឋកិច្ចរបស់វា នៅតែជាបញ្ហាប្រឈមដ៏ចម្បងខាងផ្នែកវិទ្យាសាស្ត្រ និងគោលនយោបាយ។

និក្ខេបបទស្រាវជ្រាវនេះ មានគោលបំណងវាយតម្លៃពីរបៀបនៃការផ្លាស់ប្តូរការប្រើប្រាស់ដី ដែលធ្វើឲ្យមានការប្រែប្រួលជីវចម្រុះរបស់ព្រៃត្រូពិច រួមជាមួយនឹងសេវាកម្មប្រព័ន្ធអេកូឡូស៊ី និងតម្លៃសេដ្ឋកិច្ចនៃកាបូនរបស់វា ដោយប្រើប្រាស់នូវទិន្នន័យអង្កេតអេកូឡូស៊ីដែលប្រមូលបាននៅទីវាល រួមផ្សំជាមួយនឹងទិន្នន័យវិភាគតាមផ្កាយរណប ដែលត្រូវបានសិក្សានៅក្នុងតំបន់ការពារធម្មជាតិនៃប្រទេសកម្ពុជា។ ការស្រាវជ្រាវនេះ រួមបញ្ចូលការសង្កេតយ៉ាងលម្អិតអំពីរចនាសម្ព័ន្ធព្រៃឈើ(stand structure) នានាភាពនៃប្រភេទ(species diversity) លក្ខណៈមុខងារ(functional traits) និងលក្ខខណ្ឌដីនៃស្ថានប្រព័ន្ធព្រៃឈើផ្សេងៗគ្នា រួមបញ្ចូលជាមួយនឹងការផ្គូផ្គងផែនទីគម្របដី ដែលបង្កើតឡើងដោយប្រើម៉ាស៊ីនស្វ័យសិក្សា(machine learning) ចាប់ពីឆ្នាំ១៩៩១ ដល់២០២១ ការប្រើប្រាស់ម៉ូឌែលជលសាស្ត្រ ការវាយតម្លៃបរិមាណរក្សាទុកកាបូន និងតម្លៃសេដ្ឋកិច្ចរបស់វា ដែលពាក់ព័ន្ធនឹងគម្រោងរេដបូក(REDD+)។ ការធ្វើសមាហរណកម្មនៃវិធីសាស្ត្រទាំងនេះរួមបញ្ចូលគ្នា ជាវិធីសាស្ត្រ

សមស្របមួយ ដែលអាចអនុញ្ញាតឱ្យយើងធ្វើការវាយតម្លៃការផ្លាស់ប្តូរប្រព័ន្ធអេកូឡូស៊ីទៅតាមទំហំមាត្រដ្ឋាន និងពេលវេលានៃការសិក្សាផ្សេងៗគ្នា។

លទ្ធផលបង្ហាញថា ការបម្លែងពីព្រៃចាស់ដែលមានសភាពល្អ ទៅជាព្រៃដុះឡើងវិញ ឬចម្ការស្វាយចន្ទី បណ្តាលឱ្យមានការខូចខាតនៃប្រព័ន្ធអេកូឡូស៊ីរបស់ព្រៃឈើ។ ភាពសម្បូរបែបនៃប្រភេទ ភាពចម្រុះនៃលក្ខណៈមុខងារ រចនាសម្ព័ន្ធព្រៃឈើ បរិមាណជីវម៉ាសលើដី និងលក្ខខណ្ឌដី សុទ្ធតែថយចុះទៅតាមលំនាំនៃការប្រែប្រួលគម្របដី ក្នុងខណៈដែលព្រៃចាស់នៅតែបង្ហាញពីភាពល្អប្រសើរបំផុតនៃអេកូឡូស៊ីព្រៃឈើរបស់វា បើប្រៀបទៅនឹងព្រៃដុះឡើងវិញ ឬចម្ការស្វាយចន្ទី។ លំនាំទាំងនេះ ត្រូវបានបង្ហាញនៅកម្រិតតំបន់ទេសភាព ដោយក្នុងកំឡុងពេលបីទសវត្សរ៍នៃការទន្រ្ទានព្រៃឈើ គួបផ្សំជាមួយភាពមានកម្រិតក្នុងការស្តារព្រៃឈើឡើងវិញ និងការពង្រីកផ្ទៃដីដាំដុះចម្ការស្វាយចន្ទីយ៉ាងឆាប់រហ័ស បាននឹងកំពុងគំរាមកំហែងតំបន់ទេសភាពភ្នំគូលែនឲ្យក្លាយទៅទីជម្រាករវាងតំបន់ព្រៃនិងដំណាំកសិកម្មចម្រុះលាយឡំគ្នា (Mosaic) ដែលជាហេតុធ្វើឲ្យមានការព្រួយបារម្ភជាខ្លាំងទៅលើជីវចម្រុះ និងមុខងារប្រព័ន្ធអេកូឡូស៊ីនៅក្នុងតំបន់ព្រៃចាស់ដែលនៅសេសសល់ក្នុងតំបន់ឧទ្យានជាតិ។

ការវិចវិលនៃអេកូឡូស៊ីទាំងនេះ បានបង្ហាញដោយផ្ទាល់ពីការធ្លាក់ចុះនៃសេវាកម្មប្រព័ន្ធអេកូឡូស៊ីនៅក្នុងតំបន់ទេសភាពភ្នំគូលែន។ បរិមាណរក្សាកាបូននៅក្នុងតំបន់បានធ្លាក់ចុះ ដោយសារការបាត់បង់និងការទន្រ្ទានព្រៃឈើ លើសពីអ្វីដែលព្រៃដុះឡើងវិញអាចផ្តល់ឱ្យបាន ដែលជាហេតុនាំឱ្យមានការថយចុះជាបន្តបន្ទាប់នៃបរិមាណកាបូនស្តុករបស់ព្រៃឈើនៅក្នុងតំបន់។ មុខងារនិយ័តកម្មធនធានទឹកក៏ត្រូវបានប៉ះពាល់ផងដែរ ដោយសមត្ថភាពក្នុងការធ្វើនិយ័តកម្មធនធានទឹកនៅរដូវប្រាំងត្រូវបានថយចុះ។ លើសពីនេះ ព្រៃដុះឡើងវិញ និងប្រភេទដំណាំចម្ការ មិនអាចបំពេញជំនួសនូវការបាត់បង់ព្រៃចាស់ធម្មជាតិ ក្នុងរយៈពេលខ្លីត្រឹមប៉ុន្មានបីទសវត្សរ៍នោះបានឡើយ។ កត្តាទាំងនេះ បានបង្ហាញពីតួនាទីយ៉ាងសំខាន់ និងមិនអាចជំនួសបានរបស់ព្រៃចាស់ក្នុងការរក្សាទុកបរិមាណកាបូន និងនិយ័តកម្មធនធានទឹក។

នៅពេលដែលយើងគិតអំពីតម្លៃនៃសេដ្ឋកិច្ច បំរែបំរួលនៃជីវរូបសាស្រ្តខាងលើ មានផលប៉ះពាល់យ៉ាងធំធេងចំពោះសង្គមជាតិ។ ខណៈព្រៃចាស់តំណាងឱ្យមូលធនធម្មជាតិ ដែលមានតម្លៃខ្ពស់សម្រាប់ការកាត់បន្ថយឥទ្ធិពលនៃការប្រែប្រួលអាកាសធាតុនិងការផ្គត់ផ្គង់សេវាកម្មប្រព័ន្ធអេកូឡូស៊ី មានការធ្លាក់ចុះនៃបរិមាណជីវម៉ាសនិងបរិមាណរក្សាកាបូនព្រៃឈើរបស់វាបាននឹងកំពុងកាត់បន្ថយនូវឱកាសទទួលបាននូវហិរញ្ញទានកាបូនពីការប្រែប្រួលអាកាសធាតុ

រួមទាំងប្រាក់ចំណូលរយៈពេលវែងទៅដល់សហគមន៍និងរាជរដ្ឋាភិបាល។ លទ្ធផលនៃការសិក្សានេះ បានបង្ហាញថា ការពន្យាពេលក្នុងការមិនអភិរក្សព្រៃចាស់ដែលនៅសេសសល់ទាំងនោះទេ មិនត្រឹមតែបណ្តាលឱ្យមានការខូចខាតនូវប្រព័ន្ធអេកូឡូស៊ីតែប៉ុណ្ណោះទេ ថែមទាំងនាំឱ្យបាត់បង់នូវផលប្រយោជន៍សេដ្ឋកិច្ចយ៉ាងសំខាន់ផងដែរ។

សរុបជារួម និក្ខេបបទស្រាវជ្រាវនេះ បង្ហាញថាការសិក្សាអំពីស្ថានភាពព្រៃឈើ មិនគួរត្រូវបានគិតគូរត្រឹមតែពីទំហំព្រៃឈើដែលមាននោះទេ ប៉ុន្តែគួរតែគិតបញ្ចូលទាំងមុខងារប្រព័ន្ធអេកូឡូស៊ី(ecosystem functioning) និងការផ្គត់ផ្គង់សេវាកម្មប្រព័ន្ធអេកូឡូស៊ីរយៈពេលវែងរបស់វាផងដែរ។ ដូច្នេះ ការសម្រេចចិត្តក្នុងការប្រើប្រាស់ដី អាចប៉ះពាល់ដល់បំរែបំរួលជីវចម្រុះ ការរក្សាទុកកាបូន ការធ្វើនិយ័តកម្មធនធានទឹក និងតម្លៃសេដ្ឋកិច្ចដែលធនធានព្រៃឈើអាចផ្តល់ឱ្យយើង។ ការការពារព្រៃចាស់តំបន់ត្រូពិចឱ្យមានសភាពល្អ គឺជាយុទ្ធសាស្ត្រដែលមានប្រសិទ្ធភាពខ្ពស់បំផុត ក្នុងការរក្សាលំនឹងប្រព័ន្ធអេកូឡូស៊ី ក៏ដូចជាអត្ថប្រយោជន៍រយៈពេលយូរអង្វែងសម្រាប់សង្គមជាតិ ហើយគួរតែត្រូវបានផ្តល់អាទិភាពជាចម្បង ជាជាងការគិតគូរតែពីផលប្រយោជន៍រយៈពេលខ្លីនៃការប្រើប្រាស់ដី ក្នុងការធ្វើគោលនយោបាយអភិរក្ស និងការគ្រប់គ្រងធនធានដីធ្លី។

List of papers

Paper I

Sovann, C., Tagesson, T., Vestin, P., Sakhoeun, S., Kim, S., Kok, S., & Olin, S. (2025). Land-Cover Change Alters Stand Structure, Species Diversity, Leaf Functional Traits, and Soil Conditions in Cambodian Tropical Forests. *Biogeosciences*, *22*(18), 4649-4677. https://doi.org/10.5194/bg-22-4649-2025

Paper II

Sovann, C., Olin, S., Mansourian, A., Sakhoeun, S., Prey, S., Kok, S., & Tagesson, T. (2025). Importance of Spectral Information, Seasonality, and Topography on Land-Cover Classification of Tropical Land-Cover Mapping. *Remote Sensing*, *17*(9), 1551. https://doi.org/10.3390/rs17091551

Paper III

Sovann, C., Tagesson, T., Chim, L., Mot, L., Vestin, P., Sakhoeun, S., Kim, S., Kok, S., & Olin, S. Impact of Land-Cover Changes from 1991 to 2021 on Supply of Hydrological Services and Carbon Storage of a Tropical Forest Landscape. Manuscript in preparation

Paper IV

Chou, P., Fujikawa, K., **Sovann, C.**, Khorn, V., & Chhinh, N. (2025). Economic Valuation of Forest Carbon Storage and REDD+ Readiness: Insights from Virachey National Park, Cambodia. *Asian Economic Papers*, 1-24. https://doi.org/10.1162/asep.a.8

Author's contribution to the papers

Paper I

Sovann, C.: conceptualization, investigation, data curation, formal analysis, visualization, writing—original draft preparation, writing—review and editing; Tagesson, T.: conceptualization, writing—review and editing, supervision, funding acquisition; Vestin, P.: conceptualization, writing—review and editing, supervision; Sakhoeun, S.: investigation, resources; Kim, S.: investigation; Kok, S.: investigation, supervision, funding acquisition; Olin, S.: conceptualization, writing—review and editing, supervision, funding acquisition.

Paper II

Sovann, C.: conceptualization, methodology, software, formal analysis, investigation, data curation, writing—original draft preparation, writing—review and editing, visualization; Olin, S.: conceptualization, methodology, writing—review and editing, supervision, funding acquisition; Mansourian, A.: methodology, writing—review and editing, supervision; Sakhoeun, S.: investigation, resources; Prey, S.: software, data curation; Kok, S.: resources, writing—review and editing, supervision, funding acquisition; Tagesson, T.: conceptualization, methodology, writing—review and editing, supervision, funding acquisition.

Paper III

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Paper IV

Chou, P.: conceptualization, methodology, formal analysis, investigation, data curation, writing—original draft preparation, writing—review and editing, visualization; Fujikawa, K.: conceptualization, methodology, writing—review and editing, supervision, funding acquisition; **Sovann, C.**: methodology, formal analysis, writing—original draft preparation, writing—review and editing, visualization; Khorn, V.: investigation, writing—review and editing; Chhinh, N.: conceptualization, methodology, formal analysis, investigation, writing—original draft preparation, writing—review and editing.

Abbreviations

AGB	Aboveground biomass
DBH	Diameter at breast height
GPS	Global Positioning System
LAI	Leaf area index
NBR	Normalized Burn Ratio
NDVI	Normalized Difference Vegetation Index
REDD+	Reducing Emissions from Deforestation and Forest Degradation and the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks
SWAT	Soil and Water Assessment Tool
UNESCO	United Nations Educational, Scientific and Cultural Organization

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Introduction

1.1 Global importance of tropical forests for ecosystem services

Rapid population growth, coupled with rising consumption, is intensifying global demands for food, water, and energy, placing unprecedented pressure on natural ecosystems and the services essential to human well-being (Llopis et al., 2022; Sethi et al., 2022). Climate change further amplifies this pressure by altering temperature and precipitation regimes, thereby affecting agricultural productivity, freshwater availability, and the feasibility of low-carbon energy sources such as biofuels (Yang et al., 2024). These combined pressures are primarily expressed through land-use and land-cover change, including deforestation, agricultural intensification, and urban expansion, which fundamentally alter forest ecosystem structure and functioning (Madrigal-Martínez & Miralles i García, 2019; Duan et al., 2024). As a result, maintaining ecosystem-service integrity has become central to both environmental sustainability and long-term human well-being.

Within this global context of escalating environmental pressure, tropical forest ecosystems emerge as one of the most critical yet vulnerable systems for sustaining biodiversity and ecosystem services. Tropical forest ecosystems, in particular, are highly vulnerable to these changes, with nearly half of their original extent already lost due to human activities (Muche et al., 2023). Tropical forests cover approximately 14% of the Earth's surface (Fichtner & Härdtle, 2021) and contribute significantly to global terrestrial biodiversity (Giam, 2017) and biogeochemical cycles (Males et al., 2022). They also account for at least 30% of the global terrestrial net primary production (Townsend et al., 2011; Joseph Wright, 2013) and approximately 70% of the global gross carbon sink (Pan et al., 2024). These attributes position tropical forests as a foundation of global ecosystem-service supply, linking local biophysical processes to regional and global human benefits. However, this capacity is increasingly reduced by accelerating global land-use changes, including deforestation, agricultural expansion, and urbanization, which have led to substantial losses in forest cover and diminished service provision (Mo et al., 2023).

The societal relevance of tropical forests is most clearly understood through the ecosystem services they generate and sustain. Ecosystem services are the benefits that nature provides to human well-being, supporting livelihoods, economic growth, and global environmental stability (Millennium Ecosystem Assessment, 2005). These services come from biophysical processes such as primary productivity, nutrient cycling, water regulation, and carbon sequestration, and they enable food production, climate regulation, flood mitigation, and soil fertility. Forest ecosystems, particularly tropical forests, are among the most critical global providers of these services due to their biodiversity hotspots, structural complexity, and capacity to store vast amounts of carbon and are vital to regulate water and climate (Costanza et al., 1997). Forests also supply cultural, spiritual, and recreational values that are central to many societies (Nolander & Lundmark, 2024). However, anthropogenic land-use and land-cover changes continue to put considerable pressure on these vital ecosystems, leading to declines in biodiversity, alterations in hydrological regulations, and reductions in carbon sequestration capacity (Guarderas et al., 2022; Hasan et al., 2025).

1.2 Linking land-cover changes to ecosystem-service supply

Translating the ecological importance of tropical forests into societal relevance requires understanding how land-use and land-cover change alters the processes that sustain ecosystem services (Fig. 1). Land-cover change modifies the biophysical processes that sustain biodiversity, ecosystem functioning, and ultimately ecosystem-service supply (Gomes et al., 2020). When forests are altered or replaced by agriculture and plantations, the composition, structure, and spatial arrangement of vegetation shift, disrupting ecological processes that underpin carbon storage, hydrological regulation, and habitat provision (Toro et al., 2022). These changes emerge through three tightly connected pathways: declining species diversity, altered stand structures, and shifts in functional traits.

Biodiversity, particularly species diversity, is a fundamental aspect of how forest ecosystems function, crucial for maintaining the supply of services and enhancing resilience against disturbances and climate change (Hisano et al., 2018). Variation in species richness, evenness, and functional diversity determines how communities use resources, respond to disturbance, and maintain productivity (Tilman & Downing, 1994; Díaz & Cabido, 2001).

Functional diversity, an aspect of biodiversity, is a measure of differences in leaf traits, phenology, wood density, and physiological strategies and often explains ecosystem functioning more strongly than species richness alone, because it reflects how species differences translate into complementary resource use and resilience (Loreau, 1998; Cadotte et al., 2011; Migliavacca et al., 2021). In intact tropical forests, diverse trait combinations enable efficient light capture, sustained productivity, and stable nutrient cycling (Aguirre-Gutiérrez et al., 2025). When forests are degraded or converted to regrowth or plantation systems, functional redundancy declines, niche space narrows, and communities become dominated by fewer species with similar traits (Aguirre-Gutiérrez et al., 2022). These shifts reduce ecosystem capacity to support key functions, including biomass growth, litter decomposition, and regeneration. By limiting the diversity of traits that govern energy and nutrient processing, such changes directly link biodiversity loss to diminished ecosystem functioning.

Stand structure is another dimension of biodiversity that describes the physical characteristics of forest ecosystems and provides additional control over ecosystem functioning (Wang et al., 2024). Attributes such as tree height distribution, diameter variation, stem density, and basal area determine light interception, microclimate regulation, and competitive interactions (McElhinny et al., 2005). Structurally complex forests with large trees and multilayered canopies support greater carbon stocks, stronger evapotranspiration, and more stable hydrological processes (Ali, 2019; Soto et al., 2024). Fragmentation and land-cover transitions simplify these structures, lowering biomass, increasing exposure to edge effects, and reducing regeneration potential (Forzieri et al., 2022). Such structural simplifications diminish forest functioning by reducing productivity, altering nutrient cycling, and weakening resistance to climatic stress (Bourgoin et al., 2024; Marsh et al., 2025).

Together, species richness, functional traits, and structural attributes regulate the ecosystem functions that form the foundation of ecosystem services (Tilman et al., 2014). Ecosystem functions such as productivity, nutrient cycling, water regulation, and carbon sequestration emerge from underlying ecological processes (Lovett et al., 2005). When land-cover change erodes species and trait diversity or simplifies stand structure, the capacity of ecosystems to perform these functions declines (Keith et al., 2022). Regulation functions such as carbon storage and hydrological regulation weaken when biomass declines and evapotranspiration patterns change (Keith et al., 2022; Kull et al., 2024). Habitat functions decline as species lose suitable niches. Production functions, such as timber and non-timber forest products, decline with lower productivity. Information and cultural functions are also diminished as natural landscapes become fragmented and simplified (Leemans & De Groot, 2003). These functional declines cascade into reduced ecosystem-service supply.

Furthermore, these biophysical changes also have direct economic implications. Carbon stored in forests represents not only a regulating service but also a quantifiable economic asset within voluntary and compliance carbon markets (Nolander & Lundmark, 2024). When land-cover change reduces biomass and carbon density, it diminishes opportunities for climate finance and reduces potential revenues for communities and governments (Raihan, 2023; Nolander & Lundmark, 2024). Mechanisms such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation and the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks) link ecosystem function (carbon sequestration) to monetary value, enabling financing for conservation, forest monitoring, and local livelihoods. In Cambodia, forests hold significant carbon storage potential, and their degradation threatens not only ecosystem integrity but also opportunities to secure results-based payments and long-term conservation funding (Ministry of Environment (Cambodia), 2020). Therefore, ecosystem degradation creates both ecological and economic losses, making valuation essential for understanding the full consequences of land-cover change. Despite strong theoretical understanding that species diversity, functional traits, and stand structure jointly regulate ecosystem functioning and ecosystem-service supply, empirical evidence from tropical forests remains fragmented (Sovann et al., 2025b). Integrated field-based assessments that simultaneously compare intact forests, regrowth forests, and plantation landscapes along gradients of land-use intensity are rare, particularly in Southeast Asia (Sovann et al., 2025b). As a result, it remains poorly resolved how land-cover change alters biophysical processes and constrains ecosystem-service provision and associated economic value in rapidly transforming tropical regions.

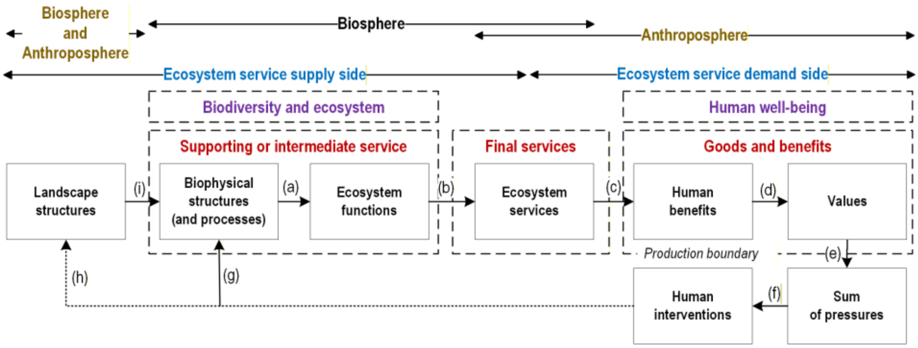

Figure 1. Conceptual framework illustrating the ecosystem-service cascade from landscape structure to human well-being (adapted from Haines-Young and Potschin (2010); Potschin-Young et al. (2018))

The model describes the interaction between environmental and social-economic systems. The environmental system is defined in this context as "Biophysical structures (and processes)," "Ecosystem functions," and "Ecosystem services"; it also encompasses their interactions (a, b). The social-economic system comprises "Human benefits" and "Values" derived from ecosystem services; it also encompasses their interaction (c, d). Furthermore, the framework shows the sum of pressures from "Values" (e) on the environmental system. These pressures will in turn influence people's actions in the landscape, changing how the land is used (f) and changing the landscape and biophysical structures (g, h).

1.3 Forest change in Southeast Asia and Cambodia

Southeast Asia, a global hotspot of rapid forest loss, faces escalating threats to the ecosystem-services supplied by its tropical forests (Schmid et al., 2021). Although the region holds about 15% of global tropical forests (Stibig et al., 2014), it has experienced the highest deforestation rates over the past two decades (Miettinen et al., 2011), and this alarming trend threatens over 40% of the region's biodiversity by 2100 (Sodhi et al., 2004). Forest loss and degradation reduce the capacity of ecosystems to provide essential services, including habitat provision, carbon storage, and hydrological regulation, all of which are fundamental to human well-being.

Deforestation in Southeast Asia is driven primarily by timber harvesting (Pearson et al., 2017), shifting cultivation, and large-scale land acquisitions for agricultural expansion, including rubber, cashew, oil palm, eucalyptus, and acacia (Grogan et al., 2015; Chen et al., 2016; Johansson et al., 2020). Although secondary forests enhance biodiversity and partially restore ecosystem services (Tito et al., 2022), they seldom attain the carbon stocks or hydrological regulatory capacity of intact forests (Bourgoin et al., 2024).

Within this context, Cambodia reflects these regional trends. Forest conversion has accelerated since the early 1990s due to population growth, expanding road networks, large-scale land acquisitions for plantations, and strong market incentives for crops such as cashew and rubber (Riggs et al., 2020; Pauly et al., 2022). These land-use transitions directly affect ecosystem services at the national scale, particularly in forested watersheds where carbon storage, groundwater recharge, and dry-season water regulation are essential for rural livelihoods and for sustaining culturally significant landscapes (Schmid et al., 2021).

Phnom Kulen and Virachey National Parks are critical examples. Situated at the headwaters of the Siem Reap River, Phnom Kulen supports evergreen and semi-evergreen forests that store carbon, maintain groundwater recharge, and regulate dry-season flows crucial for the local community and for sustaining the Angkor World Heritage site (Chim et al., 2021). However, rapid expansion of cashew plantations and other non-forest land uses has altered the characteristics of these ecosystems, raising concerns about declining carbon stocks, reduced hydrological services, and long-term reliability of ecosystem services (Chim et al., 2021). In contrast, Virachey retains some of the largest remaining intact forest blocks in Cambodia, yet has also experienced increasing pressure from illegal logging, land-use change, and socio-economic drivers over the past two decades (McCann et al., 2022; Chou & Cheb, 2023). These reflect that Cambodia’s protected forests hold significant carbon storage potential with direct economic value, and their degradation threatens not only ecosystem integrity but also long-term opportunities for international conservation and climate-mitigation finance mechanism initiatives such as REDD+ (Ministry of Environment (Cambodia), 2020). Therefore, it is essential to assess the economic value of forest carbon stocks to determine the feasibility of climate-mitigation financing and to facilitate evidence-based conservation planning in Cambodia's protected forest areas (Ministry of Environment (Cambodia), 2020).

The preceding sections show that land-use and land-cover changes alter tropical forests through coupled changes in species richness, functional traits, and forest structure, with cascading consequences for ecosystem-service supply and economic value. Cambodia’s protected forests provide a critical setting to address this gap, enabling the simultaneous comparison of intact forests, regrowth forests, and plantation landscapes along gradients of land-use intensity, while supporting nationally important hydrological and carbon services under global population growth and climate change pressures. An integrated approach linking field-based ecological measurements with remote sensing and long-term land-cover analysis is therefore required to quantify how forest conversion alters ecosystem structure, service provision, and associated economic outcomes.

Aim and objectives

The overall aim of this thesis is to quantify and to improve our understanding of how land-use and land-cover changes affect tropical forest ecosystems and the ecosystem services they provide. The thesis integrates field-based evidence of changes in forest structure, species diversity, leaf functional traits, and soil conditions (Paper I) with remote-sensing approaches for accurate land-cover classification (Paper II). It further examines how three decades of land-cover change have altered hydrological ecosystem services and carbon storage (Paper III) and links these biophysical changes to the economic value of forest carbon and Cambodia's REDD+ readiness (Paper IV). Collectively, these studies provide a comprehensive assessment of how forest conversion influences ecosystem condition, service provision, and carbon-related economic outcomes.

To achieve this overall aim, the thesis addresses four interconnected specific objectives:

1. Assess how land-cover change influences tropical forest stand structure, species diversity, leaf functional traits, and soil conditions, thereby identifying the ecological consequences of forest conversion.
2. Evaluate the role of spectral, seasonal, and topographic variables in improving land-cover classification accuracy within tropical forest–agriculture mosaics to strengthen landscape monitoring.
3. Quantify the impacts of land-cover change from 1991 to 2021 on hydrological ecosystem services and carbon storage, providing long-term insights into how ecosystem-service supply responds to ongoing landscape transformation.
4. Determine the economic value of forest carbon storage and assess Cambodia's REDD+ readiness, linking carbon stock estimates to policy-relevant frameworks for conservation and climate mitigation.

Methods

Study area

Cambodia serves as the national context for all four papers in this thesis. The country lies between 10° and 15° north and 102° and 108° east in mainland Southeast Asia and shares a border with Thailand, Laos, Vietnam, and the Gulf of Thailand (Fig. 2). Its physical geography ranges from lowlands around the Mekong River and the Tonle Sap Lake system, the largest freshwater ecosystem in Southeast Asia, to sandstone plateaus in the northeast and mountain ranges in the southwest and northwest that rise to 1,813 m at Phnom Aural (Gupta, 2005). Cambodia has a tropical monsoon climate that is affected by the southwest monsoon from May to October and the northeast monsoon from November to April. This causes rainfall to vary from about 1400 mm in the central plains to almost 4,000 mm in the southwestern coastal or mountainous areas (Gupta, 2005; Thoeun, 2015). The mean annual temperature is about 28 °C (Thoeun, 2015). Forest types include evergreen, semi-evergreen, deciduous, bamboo, and flooded forests, but national forest cover has declined due to agricultural expansion, infrastructure development, and plantation growth (Ministry of Environment (Cambodia), 2020; Pauly et al., 2022). These biophysical and socioecological gradients create strong variation in hydrology, carbon storage, and forest condition, making Cambodia an appropriate setting for investigating how land-use and land-cover changes alter ecosystem services in tropical forests.

Phnom Kulen National Park is the primary study area for Papers I, II, and III (Fig. 2). The park is located about 40 km northeast of Angkor in Siem Reap Province and covers 37,380 ha of Jurassic to Cretaceous sandstone plateaus that rise to 500 m (Geissler et al., 2019). The area receives about 2,290 mm of annual rainfall (Sovann et al., 2025b) and in 2021 supported evergreen, semi-evergreen, deciduous, bamboo, and regrowth forests that together covered about 72 percent of the landscape (Sovann et al., 2025a). As the headwaters of the Upper Siem Reap River, Kulen maintains the downstream water supply and supports the hydrological system of Angkor Wat, a UNESCO World

Heritage Site (Chim et al., 2021). The park and its 10 km buffer have experienced rapid land-use transitions driven by selective logging, smallholder expansion, and widespread cashew plantation establishment, causing forest loss (Chim et al., 2019). This ecologically diverse and multi-use landscape provides an ideal setting for improving land-cover classification (Paper II), examining how land-cover conversion alters stand structure, species diversity, leaf functional traits, and soil conditions (Paper I), and reconstructing multi-decadal land-cover change to quantify hydrological and carbon storage responses (Paper III).

Virachey National Park is the study area for Paper IV. It is Cambodia's largest protected area, covering 332,500 ha across Ratanakiri and Stung Treng provinces (McCann et al., 2022). The park forms part of the Indochina dry evergreen forest ecoregion and lies within the Indo-Burma biodiversity hotspot (Olson et al., 2001; Trod et al., 2020). Virachey contains large intact forest blocks and supports evergreen, semi-evergreen, mixed deciduous, bamboo, and upland grassland vegetation (Baird & Dearden, 2003), along with habitats of rare and endemic mammals, birds, and herpetofauna (Roberts et al., 2024). The local indigenous communities depend heavily on forest resources and actively engage in local management, showing clear willingness to participate in incentive-based conservation such as REDD+ (Chou & Cheb, 2023). These features make Virachey well suited for assessing aboveground carbon storage and its economic value in one of Cambodia's least fragmented forest systems.

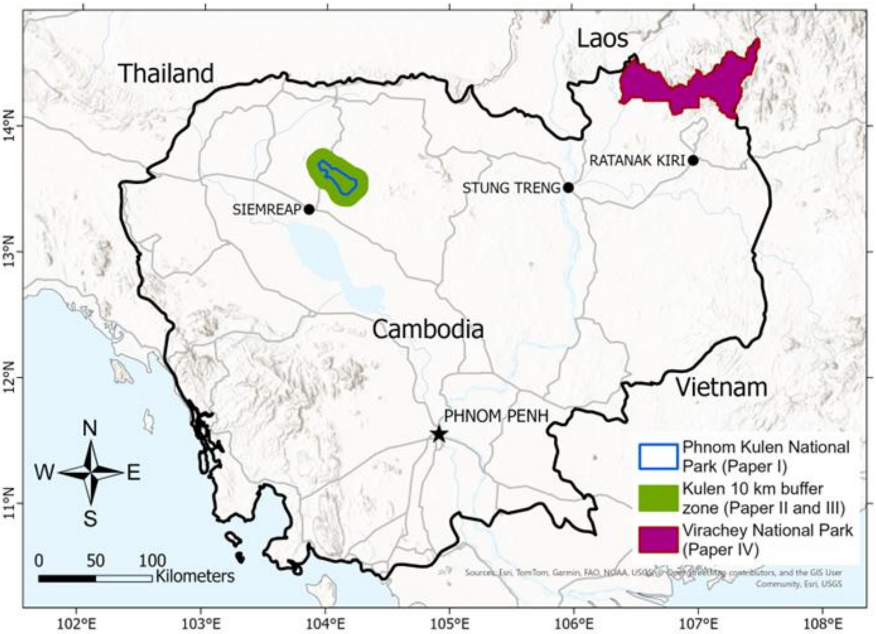

Figure 2. A map of Cambodia with the study areas of the four papers of this thesis.

Overview

This thesis integrates field ecology, satellite remote sensing, land-cover classification, disturbance detection, ecosystem-service modelling, and economic valuation to understand how land-cover change affects ecosystem structure, function, and services in two tropical forest landscapes in Cambodia: Phnom Kulen National Park and Virachey National Park. The methodological design follows a sequential and mutually reinforcing structure in which each analytical component builds on and strengthens the interpretation of those that follow (Fig. 3).

Paper I establishes the ecological foundation by quantifying forest stand structure, species diversity, leaf functional traits, and soil conditions across distinct land-cover ecosystems. These field-based measurements provide essential context for interpreting variation in biodiversity and aboveground biomass among the three land-cover types.

Paper II scales these plot-level ecological insights to the landscape by applying machine-learning methods to Sentinel-2 imagery to map the current distribution and extent of land-cover types. This classification provides an up-to-date spatial baseline characterizing ecosystem heterogeneity across the Kulen landscape.

Paper III extends the analysis into the temporal domain by using a multi-decadal time series of satellite data to reconstruct land-cover changes and assess its impacts on carbon storage and hydrological ecosystem-service supply. This temporal assessment uses the land-cover baseline from Paper II to track land-cover change over time and applies the ecological information from Paper I to interpret how these changes influence carbon storage and hydrological ecosystem-service supply.

Paper IV complements the first three papers by applying the framework to a second landscape, Virachey National Park, where it analyzes land-use change and its drivers, quantifies forest carbon stocks, and adds an economic valuation component that was not included in Papers I–III. This extension links land-cover change to carbon market value and completes the progression from ecological assessment to ecosystem-service valuation.

These components form an integrated assessment framework that moves from ecological measurement to landscape mapping, temporal change analysis, and ecosystem-service valuation. This integration ensures methodological consistency and supports a robust assessment of how forest conversion influences ecosystem functions and economic value.

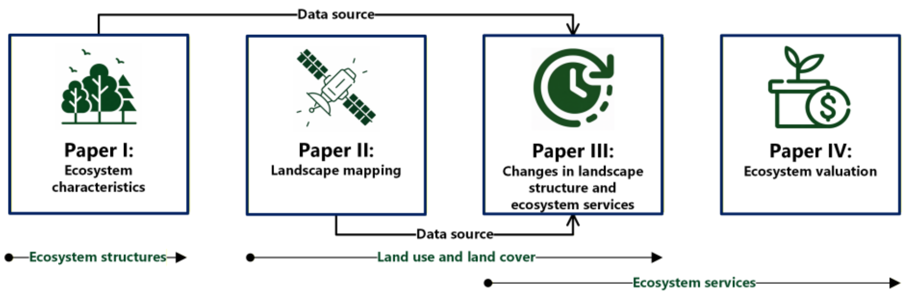

Figure 3. Workflow linking Papers I–IV through the ecosystem-services cascade from land cover and ecosystem structure to ecosystem services and economic value.

Paper I: field measurements of ecosystem characteristics

Field data were collected from nine 50 × 30 m forest inventory plots representing evergreen forest, regrowth forest, and cashew plantations in Phnom Kulen National Park. The forest inventory followed the Cambodian National Forest Inventory protocol (Than et al., 2018), recording species composition, diameter at breast height (DBH), tree height, and deadwood. Leaf functional traits were derived from samples collected from woody species, including fresh mass, leaf chlorophyll content, leaf area, and dry mass. Meteorological variables, photosynthetically active radiation, soil temperature, soil water content, and soil electrical conductivity were monitored using automated sensors. Leaf area index (LAI) was measured six times between 2019 and 2021, in both the dry season and the rainy season.

Species diversity was quantified using species richness and the Shannon–Wiener index (Shannon, 1948; Hill, 1973). Functional trait composition was assessed using specific leaf area, leaf dry matter content, and chlorophyll content, summarized as community-weighted means. Stand structure was quantified using plot-level measurements of diameter at breast height, tree height, basal area, aboveground biomass, and deadwood biomass. Aboveground biomass was estimated using locally calibrated DBH–height allometric relationships combined with species-specific wood density. Differences in ecosystem characteristics among land-cover classes were analyzed using descriptive statistics, one-way analysis of variance, and Tukey's Honestly Significant Difference. Pearson correlation and ordinary least-squares regression analyses were used to explore relationships between variables.

Paper II: classification of land cover in 2021

Sentinel-2 Level-2A imagery was used to generate annual, rainy-season, and dry-season median composites for 2021 within a 10-km buffer surrounding Phnom Kulen National Park. From these composites, spectral bands, spectral indices, tasseled cap components, and bi-seasonal differences were derived. Topographical variables were extracted from a 30 m digital elevation model (Farr et al., 2007). In total, 65 variables were assembled for subsequent variable selection and classification. Twelve land-cover classes were mapped following the Cambodian national land-cover classification (Ministry of Environment (Cambodia), 2020), with an additional cashew plantation class (Singh et al., 2019). Reference polygons used to generate training and validation datasets were derived from Global Positioning System (GPS) field points, uncrewed aerial vehicle imagery, and PlanetScope satellite imagery (Planet Team, 2017).

Land-cover classifications were performed using a Random Forest classifier (Breiman, 2001) with variable importance ranking, correlation-based filtering, and recursive feature elimination. Multiple model configurations were evaluated to quantify the contributions of spectral bands, spectral indices, bi-seasonal differences, and topographic variables, and to assess the effects of variable selection and hyperparameter tuning on classification performance. Model performance was assessed using confusion matrices reporting overall accuracy, Kappa, F1 score, user and producer accuracy, and omission and commission errors (Congalton et al., 1983; Olofsson et al., 2014). One-sided Z tests were used to compare overall accuracies and isolate the contributions of spectral indices, bi-seasonal differences, topographic variables, variable selection, and hyperparameter tuning (Zhang & Yang, 2020; Sun & Ongsomwang, 2023). The optimized classification (KuLandCover) was compared with ESA WorldCover and SERVIR-SEA land-cover products (Congalton et al., 1983; Zanaga et al., 2021; SERVIR-SEA, 2024). See Fig. 4 for an overview of the methodological workflow used in Paper II.

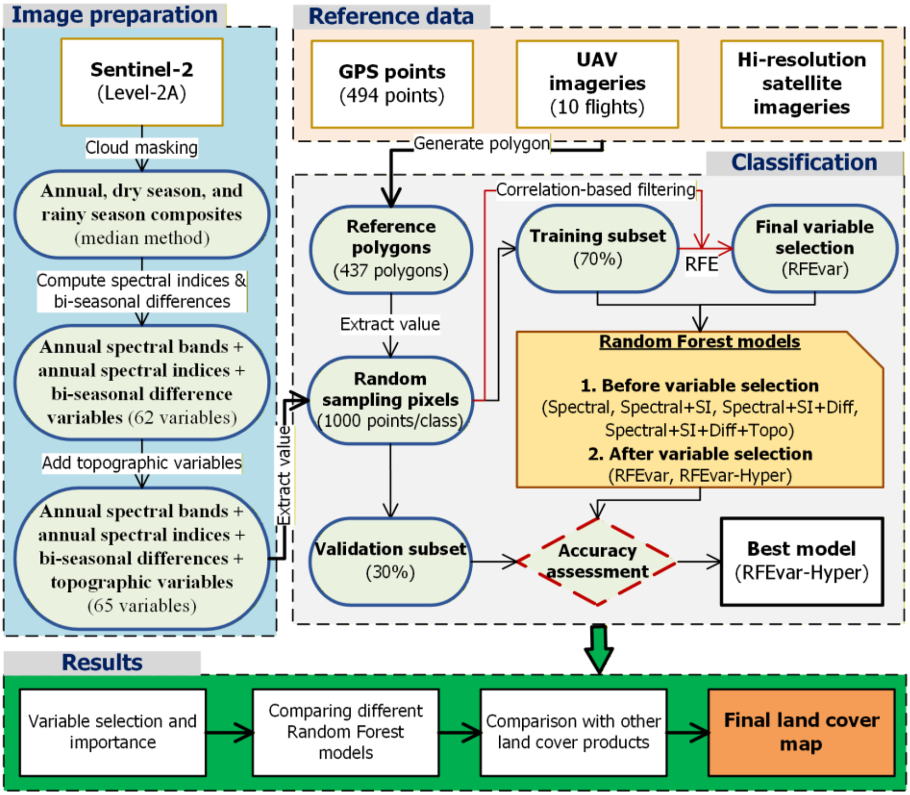

Figure 4. Overview of the methodological workflow used in Paper II.
Dashed outlines indicate major workflow sections (image preparation, reference data, classification, and results), while solid boxes represent individual processing steps within each section; arrows denote the flow of data and model outputs. The classification section summarizes image preprocessing, reference data integration, variable selection, Random Forest model training, and accuracy assessment. Six Random Forest models were evaluated to isolate the effects of input variable combinations, recursive feature elimination (RFE), and hyperparameter tuning on classification accuracy: spectral bands only (Spectral), spectral bands with spectral indices (Spectral+SI), Spectral+SI with bi-seasonal differences (Spectral+SI+Diff), Spectral+SI+Diff with topographic variables (Spectral+SI+Diff+Topo), RFE-selected variables (RFEvar), and RFEvar with hyperparameter tuning (RFEvar-Hyper).

Paper III: changes in land cover and ecosystem-service supply

Normalized Burn Ratio (NBR) time series data for 1991 to 2021 were derived from annual dry-season Landsat Surface Reflectance composites processed in Google Earth Engine, followed by the Landsat-based detection of Trends in Disturbance and Recovery (LandTrendr) algorithm (Gorelick et al., 2017; Kennedy et al., 2018). The 2021 Sentinel-2 land-cover map (Paper II) served as the baseline for reconstructing historical land-cover trajectories. Reference data for land-cover validation included manually delineated forest-loss polygons and GPS points documenting cashew plantation establishment. Hydrological data were obtained from existing Soil and Water Assessment Tool (SWAT) simulations (Chim et al., 2021). Carbon stock inputs comprised field-measured leaf area index collected between 2019 and 2021 (Paper I) and Landsat-derived Normalized Difference Vegetation Index (NDVI) time series, including monthly NDVI for 2019–2021 and dry-season NDVI for 2021, preprocessed consistently with the LandTrendr workflow (Kennedy et al., 2018).

Land-cover maps from 1991 to 2021 were generated using the LandTrendr-based breakpoint detection applied to an annual NBR time series processed in Google Earth Engine (Kennedy et al., 2018). Annual land-cover maps were generated by backcasting land-cover transitions from the 2021 classification. Changes in dry-season water yield and evapotranspiration were estimated by assigning SWAT scenario outputs to corresponding land-cover classes. Annual aboveground carbon stocks were estimated using class-specific NDVI–aboveground biomass models derived from empirical LAI–aboveground biomass relationships (Paper I), with biomass converted to carbon using a constant fraction of 0.47 (McGroddy et al., 2004). See Fig. 5 for an overview of the methodological workflow used in Paper III.

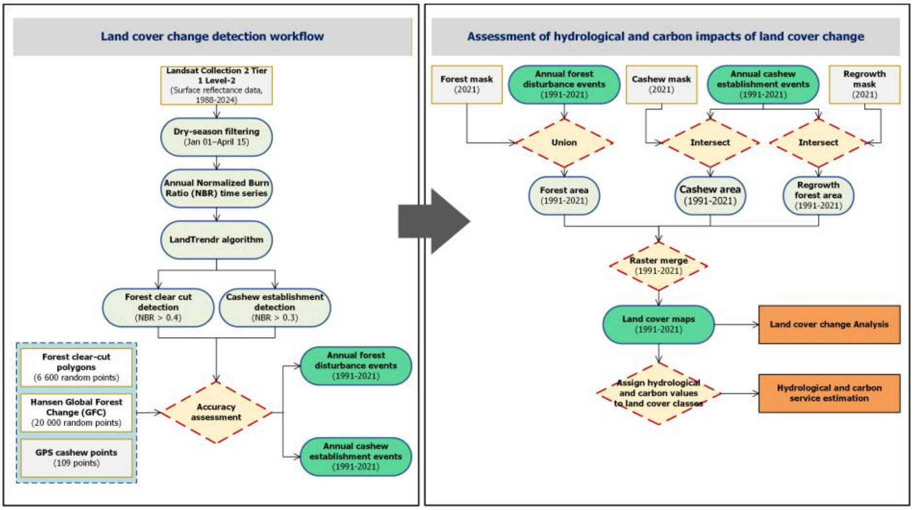

Figure 5. Overview of the methodological workflow used in Paper III.

Paper IV: carbon stock assessment and economic valuation

Land-cover datasets for 2000, 2005, 2010, 2015, and 2020 in Virachey National Park were obtained from SERVIR Southeast Asia land-cover datasets (Saah et al., 2020). Socio-institutional data were collected through key informant interviews, focus group discussions, household surveys, existing literature review, and site observations to characterize ecosystem conditions, forest management pressures, and REDD+ implementation context. Interviews were conducted with the park director, rangers, Community Protected Area representatives, and officers from Fauna & Flora, the United Nations Development Programme, BirdLife International, and Conservation International. Four focus group discussions with rangers and local villagers were conducted to explore land-cover change drivers, management capacity, REDD+ implementation hotspots, and willingness to participate in REDD+ initiatives. Household surveys were also implemented to capture socio-economic conditions, livelihood strategies, and perceptions of REDD+ participation in the landscape.

Landscape-scale carbon stocks were estimated using the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) carbon model (v3.11.0; Yang et al. (2020), Wang et al. (2025)), parameterized with land-cover-specific aboveground and belowground biomass values from national and regional data sources (Fittkau & Klinge, 1973; Mokany et al., 2006; Ministry of Environment et al., 2021). Total biomass, as the sum of aboveground and belowground biomass, was converted to carbon stocks using a constant carbon fraction of 0.47. The economic feasibility of a 20-year REDD+ project was evaluated using a cost–benefit analysis combined with a benefit-transfer approach based on data from the Tumring REDD+ project (Brander et al., 2024). Carbon revenues were estimated under multiple carbon price and discount rate scenarios to assess long-term economic outcomes and sensitivity to market variability (Ecosystem Marketplace, 2024; World Bank, 2024).

Results and discussion

Shifts in ecosystem characteristics following land-cover conversions

Land-cover conversions from evergreen forests to regrowth forests and to cashew plantations consistently reduced species diversity, diversity in leaf functional traits, structural complexity, aboveground biomass, and altered soil conditions, demonstrating a systematic degradation of ecosystem characteristics across all measured parameters (Paper I, Fig. 6).

Species diversity declined sharply along the gradient from evergreen forests to regrowth forests and was lowest in cashew plantations, as shown by reductions in species richness and Shannon–Wiener index, confirming the strong negative effect of forest conversion on community composition (Paper I). This shift reflects both the dominance of a few species in cashew plantations and the legacy of past disturbances in regrowth forests, consistent with the known sensitivity of tropical forest diversity to fragmentation and disturbance history (Whitmore, 1998; Van & Cochard, 2017). These findings demonstrate a clear loss of species diversity following a forest conversion.

Leaf functional traits showed parallel declines, with community-weighted means of specific leaf area and chlorophyll content decreasing from evergreen forests to regrowth forests and cashew plantations (Paper I). Higher community-weighted mean specific leaf area and chlorophyll content in evergreen forests reflect greater photosynthetic capacity and resource-use efficiency under dense canopies (Green et al., 2020; Guerrieri et al., 2021), whereas lower values in regrowth forests and cashew plantations are associated with reduced water and nutrient availability and increased competition, and in cashew plantations specifically, with higher temperatures that induce photoinhibition and lower chlorophyll content (Rosa et al., 2020). These patterns indicate that forest conversion reduces functional trait diversity and ecosystem productivity potential.

Stand structure was substantially simplified after conversion, with regrowth forests and cashew plantations exhibiting markedly lower DBH, tree height, and basal area than evergreen forests (Paper I). The loss of large-diameter and tall trees in regrowth forests and cashew plantations directly reflects past clear-cutting and management practices, consistent with the expectation that structural degradation reduces key ecosystem functions such as carbon storage and habitat heterogeneity (Díaz et al., 2007; Lutz et al., 2018). Stem density shifted from dominance by large trees in evergreen forests to small-diameter individuals in regrowth forests, reflecting early successional stages, while cashew plantations showed human-controlled planting densities. These patterns indicate a substantial reduction in canopy layering and spatial stand heterogeneity relative to evergreen forests.

Aboveground biomass, estimated using locally calibrated DBH–height relationships, decreased dramatically following conversion, from 312 ± 184 Mg ha^{-1} in evergreen forests to 54 ± 14 Mg ha^{-1} in regrowth forests and 17 ± 5 Mg ha^{-1} in cashew plantations. The strong DBH–height relationships in evergreen forests and regrowth forests ($R^2 = 0.92$ and 0.78) reflect natural allometric patterns shaped by species composition and disturbance history, whereas the weak relationship in cashew plantations ($R^2 = 0.51$) arises from monoculture and management practices that constrain height development. These differences demonstrate that forest conversion markedly weakens tree allometry and reduces aboveground biomass storage.

Soil conditions also shifted in response to land-cover change. Soil temperature was higher in cashew plantations due to reduced vegetation leaf canopy shielding or shading, consistent with the effects of lower interception and higher irradiance (Haren et al., 2013; Geng et al., 2022). Soil water content was lowest in regrowth forests and cashew plantations, reflecting reduced canopy cover, altered root systems, and sandier soils in cashew plantations (Ibrahim & Alghamdi, 2021; Pickering et al., 2021; Tang et al., 2021). Evergreen forests maintained the highest soil moisture and electrical conductivity due to dense vegetation and greater organic matter input (Omuto et al., 2020; Luo et al., 2023).

Land-cover conversions from evergreen forests to regrowth forests and cashew plantations resulted in consistent declines in species diversity, functional traits, stand structure, aboveground biomass, and soil microclimate, demonstrating a broad degradation of ecosystem characteristics. The simplified stand structure, weakened DBH–height allometry, and reduced community-weighted mean specific leaf area, community-weighted mean chlorophyll content, LAI, and biomass in regrowth forests and cashew plantations show that neither system approaches the structural or functional conditions of evergreen forests. These integrated shifts in composition, traits, and structure form the ecological basis for the reductions in ecosystem services quantified in the subsequent sections.

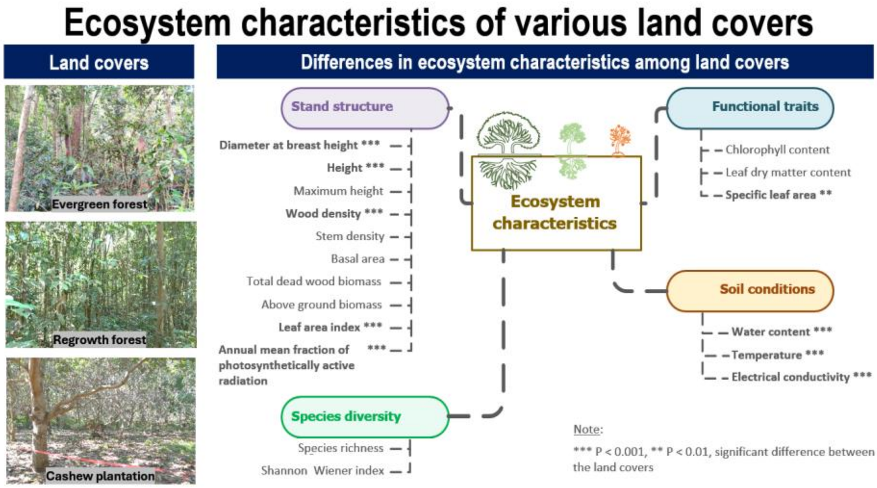

Figure 6. One-way analysis of variance summary of differences in stand structure, species diversity, functional traits, and soil conditions among evergreen forests, regrowth forests, and cashew plantations in Kulen.
Asterisks denote statistically significant differences among land-cover types (*** $p < 0.001$; ** $p < 0.01$).

Current land cover as a stock of biodiversity and ecosystem functions, and its historical change

The current land cover of the Kulen landscape reflects the accumulated effects of three decades of forest loss, or deforestation, regrowth, and agricultural expansion, forming the foundation of the present spatial distribution of biodiversity and ecosystem functions across the landscape.

The 2021 land-cover map developed in Paper II reached 92% overall accuracy by integrating spectral, bi-seasonal, and topographic variables, providing a reliable foundation for interpreting the ecosystem characteristics measured in Paper I and the functional responses analysed in Paper III. In 2021, forests covered 37% of the Kulen landscape and were concentrated in the protected national park, where forest cover reached 72%. By contrast, forest cover in the surrounding 10-km buffer was much lower, accounting for only 27% of the area.

These spatial patterns can be integrated with the ecological gradients across land-cover types identified in Paper I to examine landscape-scale variability. Areas with greater forest extent consistently show higher ecological integrity, reflected in increased species diversity, greater functional trait diversity, more complex stand structure, and higher aboveground biomass (Sovann et al., 2025b). The land-cover distribution mapped in Paper II thus provides the landscape context for understanding why the most extensively forested areas maintain the strongest ecological conditions.

Historical land-cover dynamics from 1991 to 2021 (Paper III) clarify how these present-day conditions developed. Forest cover declined from 52% to 31%, with most losses occurring in the southern and southwestern parts of the study area and continued declines inside the Kulen National Park at 0.5% per year. Cashew plantations expanded rapidly by 6.0–8.3% per year, reaching 15.4% of the protected area in 2021, while regrowth forest increased only modestly (1.5–2.2% per year).

These long-term shifts mirror the reduced species diversity, lower functional trait values, and simplified structure observed in regrowth forests in Paper I. The main drivers behind these transitions, road expansion, landmine clearance, in-migration, and adoption of cashew as a boom crop are consistent with pressures documented for Virachey National Park, where illegal logging, economic land concessions, shifting agriculture, and climate stressors have also reduced forest cover (Chanrith et al., 2016; McCann, 2016; Chou & Sovann, 2019).

A major contribution of Paper III is the explicit detection of cashew establishment years using LandTrendr ($R^2 = 0.84$), addressing a key limitation of national and global land-cover datasets that frequently misclassify cashew as forest (Paper II). This distinction is essential because cashew plantations reduce species diversity, lower functional traits, simplify canopy structure, weaken DBH–height allometry, and drastically decrease aboveground biomass (Paper I; Paper II). Without mapping cashew accurately, long-term carbon losses and hydrological declines identified in Paper III would be underestimated.

The current distribution of evergreen forest, regrowth forest, and cashew plantation and the historical processes that shaped them define the present gradient of ecosystem condition in Kulen. Evergreen forests support the highest biodiversity, structural complexity, leaf functional traits, and biomass;

regrowth forests display intermediate values; and cashew plantations represent the most simplified ecosystem state (Paper I; Paper II).

These differences determine spatial patterns of carbon storage and hydrological regulation (Paper III), while the carbon-rich intact forests also hold the highest economic value and REDD+ potential described in Paper IV (Sovann et al., 2025a). Overall, land cover is the organizing framework that links biodiversity, ecosystem functions, and socio-economic value across Cambodia's forest landscapes.

The present Kulen landscape reveals the long-term consequences of cumulative forest loss: a spatial mosaic where intact forest persists only in the protected national park while agricultural land dominates the surrounding buffer zone. This uneven configuration governs the spatial distribution of biodiversity and ecosystem services today, concentrating ecological function in remnant intact forest patches while the surrounding landscape delivers minimal contribution. The historical trajectories also show that once forests are converted to cashew plantations or degraded regrowth forests, recovery is slow and functionally incomplete, creating a persistent service deficit across the landscape.

Changes in ecosystem-service supply

Land-cover transitions in Phnom Kulen produced clear, measurable declines in carbon storage and hydrological regulation, demonstrating that structural and biological degradation described in Papers I and II has propagated directly into weakened ecosystem-function performance (Paper III, Table 1).

Carbon stocks declined steadily over the 30-year period. Total aboveground carbon in Kulen fell from 3.31 to 3.02 Tg C between 1991 and 2021 (-8.8%), driven primarily by a 13.8% (-0.46 Tg C) reduction in forest carbon, while gains in regrowth forest (+0.13 Tg C) and cashew plantations (+0.03 Tg C) were far too small to compensate for these losses (Paper III). Even inside the Kulen National Park, carbon stocks decreased by 4.6%, highlighting the persistence of forest degradation despite formal protection (Paper III). In Virachey, where forest cover remains relatively intact, total carbon storage is still high (28.42 Tg C) but has nonetheless diminished since 2000 in communes with the largest forest blocks (Paper IV).

These patterns confirm that carbon recovery in regrowth and cashew systems cannot match the density, height structure, or functional capacity of natural evergreen forests, locking in long-term deficits in carbon sequestration potential.

Hydrological services showed parallel declines. Across the Kulen watershed, dry-season evapotranspiration decreased by 2.1%, and dry-season water yield declined by 8.7% from 1991 to 2021 (Paper III). Forest evapotranspiration alone dropped by 20%, and forest contributions to dry-season water yield were reduced by 24% over the same period (Paper III). Although annual runoff appeared stable, a pattern consistent with other tropical basins experiencing forest loss (Peña-Arancibia et al., 2019; Lucas-Borja et al., 2020), the internal seasonal distribution shifted: less baseflow, weaker groundwater recharge, and more surface runoff (Paper III). Regrowth forests and cashew plantations expanded in area but not in function; their shallower roots, lower LAI, and reduced functional performance generate far weaker hydrological buffering than evergreen forest (Papers I and III).

The forests of the protected national park increasingly act as the watershed's primary hydrological refuge, even as their own functional contribution is gradually eroded (Papers I and III). These results demonstrate that carbon and water functions decline immediately and disproportionately when structurally complex evergreen forest is replaced by simplified vegetation types. The imbalance between rapid forest loss and slow regrowth recovery confirms that each year of delayed protection compounds carbon deficits and reduces hydrological stability, emphasizing the central role of intact forest in sustaining ecosystem-service supply across the Kulen landscape.

The observed declines in carbon storage and hydrological buffering confirm that the degradation of forest structure and traits translates directly into reduced ecosystem-service performance. Evergreen forests function as irreplaceable service reservoirs: neither regrowth nor cashew systems approach their carbon density, rooting depth, canopy complexity, or dry-season water regulation. The widening gap between rapid forest loss and slow functional recovery means that delays in protection lock in long-term carbon deficits and weaken watershed stability. These implications underscore that maintaining intact forests is not merely a conservation priority; it is the only viable pathway for sustaining carbon and water functions on which downstream communities and ecosystems depend. These conclusions provide the basis for evaluating the economic value, REDD+ potential, and policy relevance addressed in the subsequent sections of the thesis.

Table 1. Land-cover change and dry-season ecosystem-service responses in the Kulen watershed.
Note: Dry-season values (January–April) are reported as mean ± 95% confidence interval for the 5% and 95% forest scenarios from SWAT simulations (Chim et al., 2021). "-" indicates data not available.

Category	Metric	In this study		SWAT-based forest-cover scenario simulations from Chim et al. (2021)	
		1991 land cover	2021 land cover	95% forest scenario	5% forest scenario
Carbon storage	Carbon (Tg C)	1.56	1.45	-	-
Dry-season hydrology	Dry water yield (mil. m³)	12.72	11.61	16.02 ± 3.09	9.53 ± 1.51
	Dry evapotranspiration (mil. m³)	54.90	53.75	61.00 ± 7.45	52.58 ± 7.61
Land cover	Pristine forest (ha)	25,279	16,689	38,684	2,036
	Cashew plantation (ha)	1,729	5,869	-	-
	Regrowth forest (ha)	1,814	3,047	-	-
Hydrological stability	Coefficient of variation of annual evapotranspiration	-	-	0.36	0.41

Translating ecosystem-service supply into economic value

Ecosystem services can be translated into economic value to reveal the societal costs of forest loss and the economic rationale for conservation. While biophysical metrics quantify carbon storage, biodiversity, and hydrological regulation, these metrics only gain policy traction when framed in terms that governments, investors, and communities can act upon (Raihan, 2023). Economic valuation provides this bridge: it converts ecosystem-service performance into tangible financial terms, exposing both the benefits of intact ecosystems and the opportunity costs of degradation (Brander et al., 2024).

Paper IV demonstrates this explicitly. By valuing carbon storage in Virachey National Park through REDD+ price scenarios, the study shows that protected evergreen and semi-evergreen forests represent not just ecological assets but substantial economic capital. The park stores over 28.42 Tg C, and even when only 10% of this stock is monetized under conservative assumptions, the potential revenue ranges from US$36 million at low carbon prices to over US$350 million under high-price scenarios (Paper IV). This emphasizes the economic value of forest carbon as a long-term income stream capable of supporting local livelihoods, strengthening enforcement, and financing conservation. They also reveal the substantial financial loss associated with deforestation: every ton of carbon emitted through forest clearance represents both immediate climate damage and the destruction of future revenue potential.

This valuation linking forest condition to economic outcomes provides a powerful tool for sustainable forest management. It allows policymakers to compare the short-term profits of agricultural expansion against the long-term economic benefits of maintaining intact forests (Paper IV). It also enables communities and government agencies to justify conservation investments, negotiate REDD+ agreements, and design incentive systems that reward forest protection. When land-cover trajectories such as declining carbon stocks in Kulen or localized losses in Virachey are translated into monetary terms, the urgency of halting further degradation becomes both measurable and actionable.

The economic valuation of ecosystem services clarifies that continued forest loss is not only an ecological failure but also a financial one (Paper IV). It shows that the high-functioning evergreen and semi-evergreen forests in Kulen and Virachey are economic assets whose value far exceeds the short-term gains from conversion to cashew or shifting agriculture. Without sustained protection, the region forfeits millions of dollars in potential carbon revenue, increases long-term costs associated with water insecurity, and undermines the natural capital base on which local livelihoods depend.

Conclusion and outlook

This thesis demonstrates that sustained land-use and land-cover change drive consistent, long-term shifts in tropical forest structure and functioning, constraining their capacity to supply ecosystem services. By integrating field-based evidence of changes in forest structure, species composition, leaf functional traits, and soil conditions with high-accuracy land-cover mapping, multi-decadal land-cover reconstruction, ecosystem-service modelling, and carbon valuation, the thesis establishes land cover as an organizing state variable linking human land-use decisions to ecosystem structure, functioning, and service provision across scales. The combined results show that land-cover trajectories govern not only ecological degradation and recovery pathways but also the persistence of hydrological regulation, carbon storage, and their economic value, thereby translating ecological change into policy-relevant consequences for forest management and climate mitigation.

These findings demonstrate that land-cover trajectories structure tropical forest ecosystems in ways that extend far beyond changes in forest extent, producing persistent structural, functional, and service-level consequences. The ecological changes cause persistent long-term declines in carbon storage and hydrological regulation that regrowth forests and plantations do not fully restore compared to fully intact forests. Protecting remaining intact forests is therefore essential to sustain ecosystem services, maintain natural capital, and avoid long-term ecological and economic losses in tropical forest regions.

The conclusions of this thesis are bounded by linked uncertainties in scaling field-based evidence, resolving land-cover trajectories through time, and translating biophysical change into ecosystem service and economic estimates. Plot-based measurements provide clear insight into forest structure, functional traits, and soils, but their spatial extent limits representation of landscape heterogeneity, particularly within regrowth and plantation systems. Uncertainty in allometric models and wood-density assumptions affects absolute biomass estimates but does not alter the consistent pattern of lower carbon stocks in regrowth forests and plantations relative to evergreen forests.

Uncertainty in this thesis arises from land-cover classification, long-term reconstruction, and simplified ecosystem service and valuation models, which affect absolute estimates of biomass, ecosystem services, and carbon value but do not change the robust conclusion that forest conversion imposes long-term constraints on ecosystem-service supply.

Building on the integrated framework developed in this thesis, future research should prioritize expanding permanent field-plot networks across a wider range of tropical forest ecosystem types, including deciduous forests, to collect spatially representative measurements of forest structure, species composition, functional traits, and soil conditions that underpin ecosystem functioning and service provision. These expanded field observations should be integrated with high-accuracy, frequently updated land-cover products and long-term time-series analyses to enable robust scaling from plot-level measurements to landscape-scale estimates of biomass, ecosystem services, and carbon value.

Future studies should reduce uncertainty in carbon stock estimates. It remains a key priority that can be achieved through targeted destructive sampling or plot-scale terrestrial laser scanning combined with species-level wood-density measurements to improve locally derived allometric models.

Future research should strengthen links between ecosystem science, carbon accounting, and economic policy by developing integrated, decision-relevant metrics that translate observed ecological change into actionable information for landscape planning, conservation prioritization, and REDD+ oriented climate finance under ongoing environmental and societal change.

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