Towards a regional plan for climate change adaptation, mitigation and biodiversity conservation in Indigenous, rural, and urban landscapes of the Comox Valley

Prepared by: Jannatul Ferdous, Michelle Hak Hepburn, Ehsan Pashanejad, Ira Sutherland

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Mentor: Tim Ennis

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Disclaimer

This report was produced as part of the UBC Sustainability Scholars Program, a partnership between the University of British Columbia and various local governments and organizations in support of providing graduate students with opportunities to do applied research on projects that advance sustainability across the region.

This project was conducted under the mentorship of the Comox Valley Conservation Partnership. The opinions and recommendations in this report and any errors are those of the author and do not necessarily reflect the views of the Comox Valley Conservation Partnership or the University of British Columbia.

The authors acknowledge that the work for this project took place on the unceded ancestral lands of the K'ómoks, xwməθkwəy̓əm (Musqueam), Skwxwú7mesh (Squamish), Stó:lō and Səl̓ílwətaʔ/Selilwitulh (Tsleil- Waututh) Nations.

Author Contribution Statement

Ehsan was the lead on water-related services, Ira on carbon storage and landscape modelling, Michelle on the jurisdictional scan and policy recommendations, and Jannatul on geospatial support and data preparation.

Photo Credit

The pictures used on the cover page are taken by Francoise (Program Coordinator, CVCP), Ehsan, and Ira.

Executive Summary

Ecosystems within the Comox Valley face multiple pressures including loss of habitat through urbanization and forest management, water shortages, and the simultaneous threat of sea level rise, all of which are compounded by a changing climate. The well-being of inhabitants of the valley is inextricably tied to the health of ecosystems, which regulate the quality and timing of water, store carbon to regulate global climate, and provide places, such as old forests to visit, cool off in and re-energize themselves. However, these and other vital contributions that ecosystems make to people's wellbeing and quality of life have been historically underappreciated and often lack representation in local to regional planning. Increasing the tools for regional planning and science-based decision-making tools offers a path forward, and many jurisdictions in BC and around the world are making intentional efforts to incorporate ecosystem services into their planning and decision-making. Comox Valley currently has a strong social capacity for this type of work and the next step is to improve the basic mapping of ecosystem services, identify opportunities to improve their policy, and integrate these features into ongoing planning processes.

In the spring of 2022, four Ph.D. students were recruited by the Comox Valley Conservation Partnership as part of a UBC Sustainability Scholar program designed to leverage a collective impact of their expertise for local planning in the Comox Valley. The team, consisting of a forester, a landscape ecologist, an anthropologist, and a sustainability scientist worked collaboratively to measure ecosystem services (ES) in the Comox Valley and survey the local environmental policy within jurisdictions of the Comox Valley.

The overarching objective was to articulate principles and datasets that can advance climate change mitigation and adaptation, biodiversity conservation, natural asset management and Indigenous rights. This work will be incorporated into regional planning by (a) informing updates to Nature Without Borders, an important regional conservation strategy often consulted by municipal governments to inform land use planning; and (b) by updating the Sensitive Ecosystem Inventory, an important geospatial data layer used extensively in local decision making.

We conducted a jurisdictional scan of the municipal and First Nations policies relevant to sustainable land use and conservation in the Comox Valley (including K'ómoks First Nation, Comox Valley Regional District, City of Courtenay, Town of Comox, and Village of Cumberland). Using open-source geospatial data, we produced three ES data layers (carbon

storage, water quality and water quantity), which were chosen as some of the most important ES in the local context. To model ecosystem services, we used land cover maps and a canopy height model to estimate the age of forests as inputs. We used inVEST as our modelling platform for hydrological ecosystem services and the R programming environment for carbon storage. We also used historical landcover maps and a custom backcasting model to estimate changes in carbon storage over the past 35 years.

Since 1984, carbon storage has declined by 27%, likely because of forest management, development, and natural disturbance. In some years, approximately 300,000 tCO2 is emitted, which is roughly equal to the amount emitted from all other anthropogenic sources across the valley. Fortunately, the trend of decreasing carbon storage has slowed; since 2009, carbon storage has nearly stabilized. The preliminary carbon maps can help identify parcels of land for future park acquisition, and potentially inform strategies to help local governments achieve carbon neutrality.

Hydrological ecosystem services are essential in the Comox Valley where known concerns over water quality, sediment delivery, and seasonal water quantity (flood risk) have been raised. Our models help identify the location of water-providing areas, which account for only 15.85 % of the study area. This is important for planning and conservation purposes to know where the water originates. The model also provides seasonal variability throughout the year. Based on precipitation patterns and available water in the landscape from the SWY model we also estimated runoff retention capacity which is a proxy for inland flood risk reduction. The output represents 19.57% of the landscape with high flood risk and no runoff capacity. We linked the retention capacity of the landscape with sediment delivery output to identify a spatial indication of sediment load that can be easily carried in streams. Our results support that in general sediment yield is not high in the landscape, however, post-modelling analysis of sediment yield in SEI polygon shows areas close to Tsolum River as well as Oyster River in the northern part of the study area. This has potential negative impacts on crucial salmon habitats and for water users serviced by the Oyster River. We recommend that future research be linked with human dimensions of land use and built capital and water usage needs to further refine decision-making tools.

The outputs of these models together with additional analyses were used to define carbon and hydrological services of sensitive ecosystem inventory polygons and to identify broader patterns occurring across the landscape.

In addition to quantifying the spatial distribution of these ecosystem services, we considered policies that can support them and other conservation and restoration goals. We identified a number of innovative programs and policy directions in the Comox Valley, including discounts on development permits to encourage “green infrastructure” (Village of Cumberland); educating residents on Green Shores certifications (Comox Valley Regional District); restoration partnerships which foreground reconciliation (Kus-kus-sum project); mandating improved soil absorption capacity and a minimum pervious surface area in new development and building projects to increase water retention (Town of Comox); protecting specific native tree species, regardless of size through tree cutting bylaws (City of Courtenay); among others.

Improved data layers such as improved landcover maps and canopy height models could greatly improve the accuracy of the analysis. Meanwhile, an advantage of the datasets is that because they are freely available, this method can be easily transferred to other areas now that the methods are established.

This research, including the principles articulated and datasets produced, represents an important step towards informing strategies to better recognize and steward the incredible natural capital of the Comox Valley. The data products produced demonstrate what the authors hope is just a first step toward building more direct ways to incorporate natural capital into decision-making. This first step can help catalyze a vision of the Comox Valley as a social-ecological system characterized by close interdependencies between people and nature. Future work is needed to build out data and understand other important ecosystem services and assess the system’s resilience to future challenges. Together our scan of existing policies, data products, and recommendations establish a range of possible tools and principles to guide stewardship and development in the Comox Valley. For example, municipalities can use the spatially mapped data we have identified to inform new policy directions and explore potential Nature-Based Solutions, carbon offsets, and habitat protection opportunities.

The process has been a highly collaborative one, involving close interaction between researchers (the sustainability scholars), NGOs, and local governments of the Comox Valley. The collaborative nature of this project has informed the analysis by building off the interdisciplinary expertise and familiarity with the local context to ensure that our analysis and research directions remained relevant to conservation NGOs and municipal land use planners. This project can serve as a model for future collaborative partnerships to further landscape-level planning.

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1. Introduction

Nature Without Borders (NWB) is a regional conservation strategy, created by a partnership of conservation organizations in the Comox Valley, that has become an important resource for municipal planners. NWB was last updated in 2013. As part of a UBC Collective Impact Sustainability Scholars project, four UBC Ph.D. students - a forester, a landscape ecologist, an anthropologist, and a sustainability scientist - conducted research to inform an updated NWB. The collected data will be used to update a science-driven conservation strategy for the Comox Valley.

The Comox Valley is located on the Central-Eastern side of Vancouver Island and its entirety is within K'ómoks First Nation's traditional territory. There are three municipalities within the CVRD: the City of Courtenay, the Town of Comox, and the Village of Cumberland. The CVRD has jurisdiction over three electoral areas. K'ómoks First Nation (KFN) reserve lands are also within the CVRD political boundary. The region is heavily forested and dominated by coniferous tree species, including Douglas-fir, western hemlock, and western redcedar. Amabilis fir, mountain hemlock, and yellow cedar are common at higher elevations. In the Nanaimo Lowlands portion of the study area agriculture is an important land cover, and the area is rapidly urbanizing with the expansion of urban areas (Courtenay, Comox, and Cumberland). The ecosystems and land covers are described more fully under the section on carbon storage by ecosystem types below. One of the challenges facing biodiversity conservation in the Comox Valley is the existing fragmentation of the landscape, and that much of the land is privately owned. This requires a multi-functional approach that engages all stakeholders to ensure that the Comox Valley remains resilient and able to adapt to climate change.

We have taken a landscape approach in our evaluation of ecosystem services, prioritizing carbon and hydrological ES. A landscape approach is "any spatially explicit attempt to simultaneously address conservation and development objectives" (Sayer et al 2013: 8350). Our study area is shown in Fig. 1 and is defined by the watershed boundaries of the Oyster River, Comox Lake, and Tsable River watersheds. This study area roughly corresponds to the Comox Valley Regional District (CVRD) administrative boundary (excluding Denman and Hornby Islands because they are included in Islands Trust) but further extends to include the entirety of the Oyster River watershed which would otherwise be partially excluded based on the administrative boundary. The study area is limited to the south of the Tsable River watershed boundary, which excludes a small portion of the political boundary on the southern side.

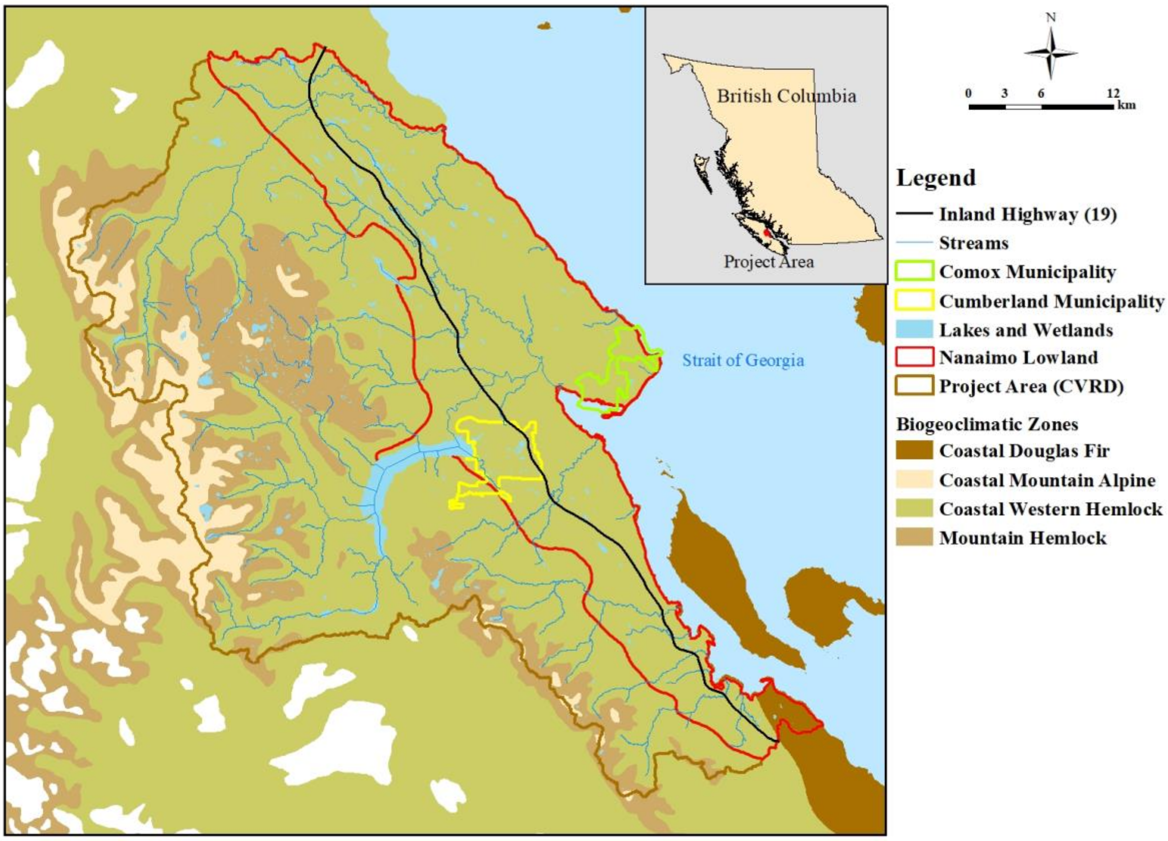

Fig. 1. Study Area Map

Linking ecosystem service assessment into policy and decision-making is a key step towards sustainable development and biodiversity conservation. Proper identification of key ecosystem service areas in support of ecosystem service assessment and management is instrumental for the policy effectiveness and conservation of biodiversity and natural resources. A sustainable approach to ecosystem management requires understanding where ecosystems provide services and where these services are delivered. Mapping ecosystem services is one way to identify ecosystem service-providing areas. Since the distribution of ecosystems and their services varies across time and space, the spatialization of ES is a key requirement to model the spatiotemporal differences regarding various drivers such as global changes and human interventions (Burkhard et al., 2012). In addition, mapping and assessing ES is essential for decision-makers to evaluate the interactions of multiple ES to appreciate landscape capacity first and then identify trade-offs and synergies of multiple ecosystem services (Rieb et al., 2017).

Carbon ES

Land management and conservation represent the key strategies to mitigate global climate change. The overarching aim of the carbon storage was to characterize the amount of ecosystem carbon storage and its spatial and temporal dynamics in the Comox Valley. This would serve as a regional carbon storage dataset that could stimulate ideas for future research. Towards this, our specific objectives were to –

- Estimate carbon-related global climate regulation services (i.e., carbon storage and carbon sequestration) of different ecosystems and land covers in the Comox Valley.

- Attribute carbon storage into the Sensitive Ecosystem Inventory (SEI) polygons mapped in the CVRD.

- Characterize the spatial and temporal dynamics in carbon-related global climate-related services in the Comox Valley.

Hydrological ES

Water ecosystems such as rivers, lakes, wetlands, and groundwater provide a variety of ecosystem services to people including drinking water, erosion prevention and soil conservation, flood retention, recreational opportunities, fisheries, and wildlife habitat (Shaad et al., 2022). However, aquatic ecosystems have been facing dramatic changes in quantity and quality due to climate change, water diversion, deforestation, land use and land cover changes, agricultural activities, and wetland loss. For water-related ecosystem services in the project, the approach is to identify key ecosystem service areas and hot spots of hydrological ecosystem services and also map the capacity of the landscape in providing ecosystem services. Water-related ecosystem services in this study are categorized as -

- Water provisioning for drinking water and other usages,
- Flood retention, and
- Erosion prevention and sediment delivery.

2. Methods

We used available geospatial data sources to estimate the hydrological ecosystem services and carbon storage of the Comox Valley. Based on these estimates we attributed the sensitive ecosystem inventory data layer to describe the density of ecosystem services provided by each SEI polygon. In addition to the geospatial analysis, we used a jurisdictional scan to understand the policy landscape and how and whether policy instruments and bylaws consider ES and contribute to biodiversity conservation.

2.1 Updating Principles, Goals, Objectives

Since Natures Without Borders (NWB) is a document representing both current conservation science and the Comox Valley Conservation Partnership (CVCP), we solicited input from the CVCP Steering Committee to inform our recommendations for updating the principles, goals, and objectives of NWB.

On June 17th, Michelle led a focus group session with the Steering Committee to gather input on previous principles, goals, and objectives of NWB (Morgan & Hoffman, 2018). Questions and definitions of terms used during the input session were informed by Conservation Measures Partnership Open Standards and by WWF Network Standards. These standards guide conservation project decision-making and help identify the logic of change for interventions. The input session was also used to better understand the social and economic context of the Comox Valley to help inform policy research directions. Michelle additionally created a follow-up survey to provide space for additional input and comments. A full discussion of the results of the input session, including the follow-up survey responses, is in a separate internal report. See Appendix C for the input session question guide.

2.2 Jurisdictional Scan

Michelle systematically searched for publications, reports, bylaws, and strategies for policy documents relevant to sustainable land use. I consulted each municipality's website to search for these documents (Town of Comox, City of Courtenay, Village of Cumberland, K'ómoks First Nation, and Comox Valley Regional District). I did not review council minutes. Many documents relevant to K'ómoks First Nation policy are not publicly available. Agreements and negotiations that K'ómoks holds with British Columbia are available on a provincial government website. I also consulted the two Tribal Council websites of which K'ómoks is or has been a member: Nanwakolas and Naut'sa mawt Tribal Council. Tribal Council websites offer an indication of types of policy documents that K'ómoks First Nation have created, but do not grant public access to these documents.

The available policy documents were then scanned for definitions and for directions that affected water management, land use, biodiversity, and other practices related to sustainable land use.

I also reviewed municipal websites for information on existing incentives or educational outreach programs related to promoting more sustainable land use (especially regarding landscaping, water conservation, green shores, and invasive species removal), and noted whether that information was easily accessible.

2.3 Best Practices

To identify best practices, we consulted existing guides for sustainable land use bylaws which include recommendations for environmental policies and best practices in British Columbia and Canada. We also consulted neighbouring jurisdictions' websites to identify existing programs and resources available to residents to promote sustainable land use practices on private land. We highlight policy actions taken by municipalities in the Comox Valley which are most aligned with and best support the principles and spirit of the NWB goals and our UBC Sustainability Scholars Project (i.e., reconciliation, conservation, and restoration). In some cases, neighbouring jurisdictions listed actions taken towards reconciliation, conservation, or restoration, but do not specify details. For example, Port Alberni states that they engage in "stream improvement projects" to improve salmon habitat. They list several watercourses that they have previously done work on but do not specify in what capacity or what was done. This makes it difficult to identify this potential work as a "best practice."

2.4 Spatial Data Sources and Pre-processing

Data Sources of Land Cover Map

Two land cover maps were identified that can be used for carbon and ecosystem modelling – one is the annual crop inventory of 2021 (https://open.canada.ca/data/en/dataset/ba2645d5-4458-414d-b196-6303ac06c1c9) (Fig. 2), and another is the land cover map of 2019 produced by Hermosilla et al. (2022) (https://opendata.nfis.org/mapserver/nfis-change_eng.html) (Fig. 3).

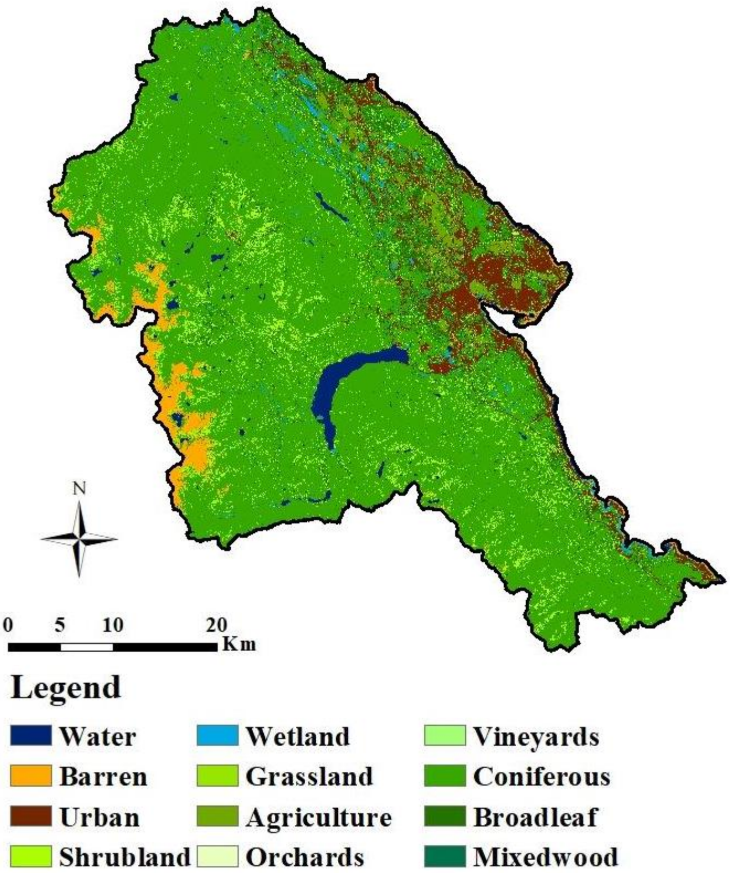

Fig. 2. Annual crop inventory 2021 for CVRD

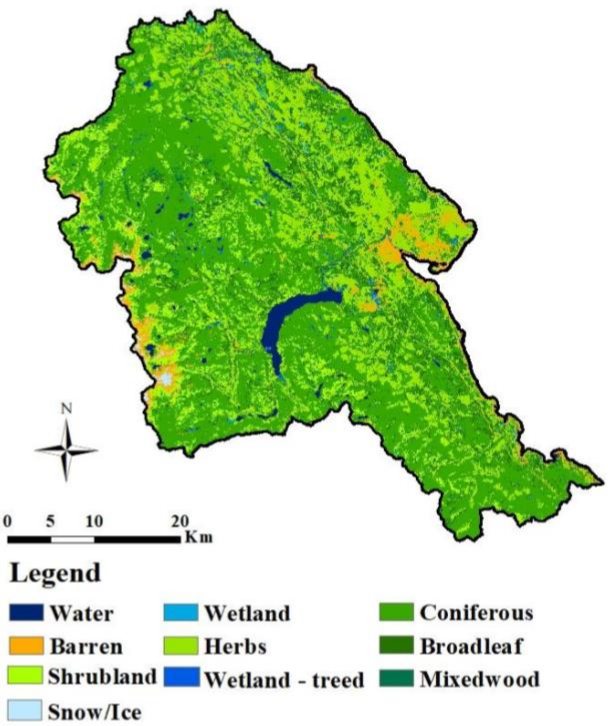

Fig. 3. Land cover map of 2019 for CVRD

Accuracy Assessment

For accuracy assessment, ground truthing was done from Google Earth images by taking 144 random points from the Nanaimo Lowland area (as this was the area of interest for updating SEI polygons and was more heterogeneous in nature) (Fig. 4). Historical images of Google Earth were used to identify ground truth values for both land cover maps. These sample points were created using the Create Random Points tool of ArcGIS. The sample size was determined based on the Binomial Probability Theory, considering 90% accuracy and 5% admissible error (Equation (1)). The formula for calculating the number of sample points is the following (Banko, 1998):

$$N = \frac{Z^2 \times p \times q}{E^2} \qquad (1)$$

Where,
N is the number of samples = 144
p is the accuracy percentage = 90%
q is 100 - p = 10%
E is the admissible error = 5%
Z is the standard deviation = 2.

From these ground truth values and land cover maps, confusion matrices were created for both land cover maps, and Producer Accuracy, User Accuracy, and Kappa Coefficient were calculated. To evaluate the individual class accuracy, Producer and User Accuracy were used. Producer Accuracy (Omission Errors) results from dividing the number of correctly classified pixels in each land cover category (on the major diagonal) by the number of reference pixels “known” to be of that category (the column total) for representing how well reference pixels of the ground cover type are classified. On the other hand, User Accuracy (Commission Error) is calculated by dividing the number of correctly classified pixels in each land cover category by the total number of pixels that were classified in that category (the row total) for representing the probability that a pixel classified into a given category represents that category on the ground (Banko, 1998). Kappa Coefficient, developed by Cohen (1960) measures the proportion of agreement after chance agreements have been removed from considerations (Equation (2)) (Banko, 1998; Bishop et al., 1975).

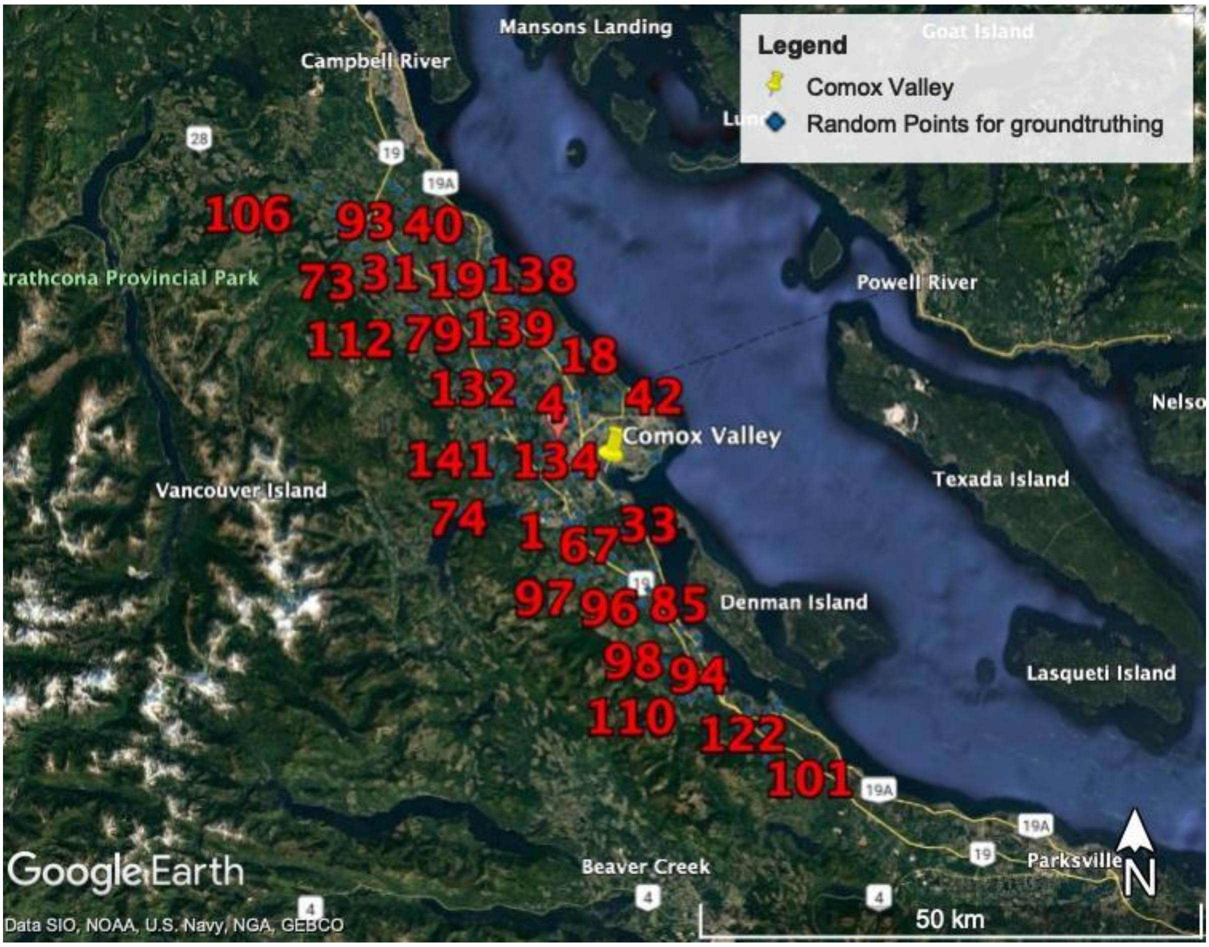

Fig. 4. Random points for ground truthing from Google Earth images

$$K = \frac{N\sum_{i=1}^{r} X_{ii} - \sum_{i=1}^{r} X_i + X_i}{N^2 - \sum_{i=1}^{r} X_i + X_i} \tag{2}$$

where,

K = Kappa Coefficient

r = number of rows and columns in the error matrix.

N = total number of observations.

X_{ii} = observation in row i and column i.

X_{i+} = marginal total of row i.

X_{+i} = marginal total of column i.

The followings are the confusion matrices for both land cover maps and computed producer and user accuracy and kappa coefficient (Table 1, 2, 3 and 4). Considering the accuracy measures and Kappa coefficient, the land cover map produced by Hermosilla et al. (2022) was selected for the base input for carbon and ecosystem modelling. Moreover, this dataset has more temporal coverage (1984-2019) than the annual crop inventory, which enables for analyzing the temporal changes in carbon storage analysis.

Table 1. Confusion matrix for annual crop inventory 2021

		Reference Data							
		Coniferous	Broadleaf	Urban/ Developed	Agriculture	Shrubland	Water	Wetland	Total
Classified Data	Coniferous	54	15	2	2	9	0	0	82
	Broadleaf	9	12	0	0	1	0	0	22
	Urban/ Developed	0	4	9	0	4	0	0	17
	Agriculture	0	0	0	7	0	0	0	7
	Shrubland	6	1	0	0	4	0	0	11
	Water	0	0	0	0	0	1	0	1
	Wetland	0	2	0	0	1	0	1	4
	Total	69	34	11	9	19	1	1	144

Table 2. Accuracy measures for annual crop inventory 2021

	User Accuracy	Producer Accuracy	Kappa Coefficient
Coniferous	65.85	78.26	
Broadleaf	54.55	35.29	
Urban/ Developed	52.94	81.82	0.42
Agriculture	100.00	77.78	
Shrubland	36.36	21.05	
Water	100.00	100.00	
Wetland	25.00	100.00	

Table 3. Confusion matrix for the land cover map of 2019 produced by Hermosilla et al. (2022)

		Reference Data							
		Herbs	Shrubs	Coniferous	Broadleaf	Water	Exposed Barren Land	Wetland-treed	Total
Classified Data	Herbs	27	5	6	7	0	8	1	54
	Shrubs	0	1	0	0	0	0	0	1
	Coniferous	1	0	46	4	0	1	0	52
	Broadleaf	0	0	17	14	0	0	0	31
	Water	0	0	0	0	1	0	0	1
	Exposed Barren Land	0	0	0	0	0	3	0	3
	Wetland-treed	0	0	0	2	0	0	0	2
	Total	28	6	69	27	1	12	1	144

Table 4. Accuracy measures for the land cover map of 2019 produced by Hermosilla et al. (2022)

	User Accuracy	Producer Accuracy	Kappa Coefficient
Herbs	50.00	96.43	
Shrubs	100.00	16.67	
Coniferous	88.46	66.67	
Broadleaf	45.16	51.85	0.49
Water	100.00	100.00	
Exposed Barren Land	100.00	25.00	
Wetland-treed	0.00	0.00	

We reclassified some mixed wood, shrubs, and herbs pixels in the landcover (LC) maps to improve accuracy for estimating ecosystem services and landscape change. The reclassification was informed by the confusion matrix, which revealed that while some land cover classes were identified relatively accurately (e.g., 88% of coniferous LC pixels were confirmed to be coniferous LC), others such as herbs LC was correctly identified at only 50% of the pixels. Herb LC included 22% of the study area and many pixels were mapped within the timber harvesting land base (THLB; areas actively managed for timber production). By comparing with aerial photographs, it was evident that herbs pixels within the THLB mostly included young forest and recently logged sites whereas herbs outside the THLB were predominantly agricultural fields and lawns. Mixed wood LC (covering 0.4% of the land base) were entirely within the THLB and appeared to predominantly represent recovering forests (at slightly higher elevations). Shrubs LC within the THLB also appeared to be young forests while shrubs LC outside the THLB were high elevation subalpine forests.

It is likely that the herbs, shrubs, and mixed wood pixels represent young conifer plantations that will continue to sequester carbon and recover to provide forest-related ecosystem services. In contrast, herbs LC outside the THLB represented lawns and agricultural fields, which have different soils and functional capacities to provide ecosystem services. Thus, we reclassified the herbs, shrubs, and mixed wood pixels within the THLB as coniferous LCs. This was done by manually delineating polygons to represent the timber harvesting land base in GIS by tracing around all visibly identifiable historical cut blocks in a 2020 aerial photo. All shrubs, herbs, and mixed wood within these polygons were reclassified as coniferous so that they would better represent the ecosystem services provided by coniferous forests and be more suitable for modelling those pixels through time. The result of this was a reduction in herbs LCs from 21.9% to 9.5%, shrubs LC from 7.6% to 3.4%, mixed wood from 0.4% to 0.03%, and an increase in coniferous LC from 52.2% to 69.1% (Appendix A, Table A1).

2.5 Estimating forest age layer for 2019

For estimating forest age, two data sources were identified as the basis of the analysis – one is the age raster derived from the Global Forest Canopy Height Model of 2019 (https://glad.umd.edu/dataset/gedi) (Fig. 5), and another is the Vegetation Resources Inventory (VRI) layer of 2019 which has an attribute for projected age (https://catalogue.data.gov.bc.ca/dataset/vri-historical-vegetation-resource-inventory-2002-2020-/resource/90149293-753e-4665-96fc-5c2ef42b1a09) (Fig. 6). Both data layers have some limitations. Age raster derived from Canopy Height Model underestimated the age (the highest pixel value was 125). On the other hand, VRI layers did not cover the whole CVRD boundary (Fig. 6). We used a height-to-age curve to translate forest height estimated from the Global Forest Canopy Height Model of 2019 (Fig. 5) into estimates of forest age for 2019. The curves were extracted from the Metro Vancouver Carbon Storage Dataset update report (Greentree, 2019) and originally derived from the forestry simulation model Forecast (Kimmins et al., 1999). The curves are for coniferous and deciduous forest types with a site index of 34, which is representative of forests within the Nanaimo Lowlands of the Comox

Valley. For the 1.5% of forest pixels that received age of NA, we manually set their ages to zero.

The height exceeded the maximum value of the age curve at roughly 6000 pixels (nearly all broadleaf), which is 32.5m for broadleaf and 53.8m for the coniferous forest. We filled in age using random number distribution for these pixels. The random numbers were bounded at the lower end by the max-age of the curve, which was 125 years for coniferous and 60 years for broadleaf. The upper end was set as 120 years for broadleaf and 150 years for coniferous based on the authors' knowledge of forest ages and disturbance history in the study area. Given that the oldest forest stands would be rarer than younger forests, a left-skewed distribution was used to generate the random ages using the sn package in R.

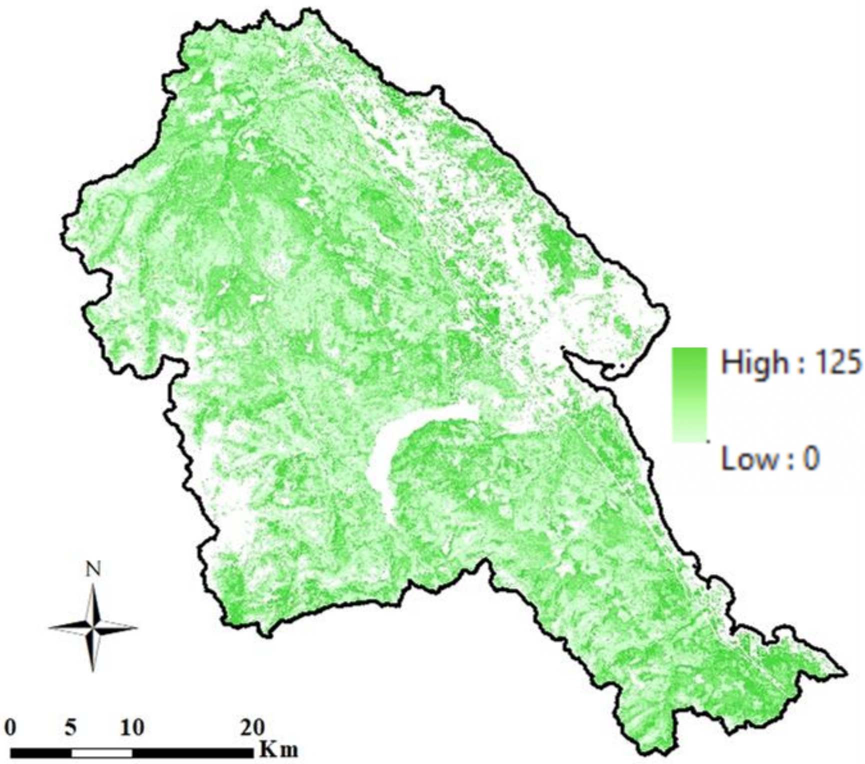

Fig. 5. Age raster derived from Global Forest Canopy Height Model of 2019

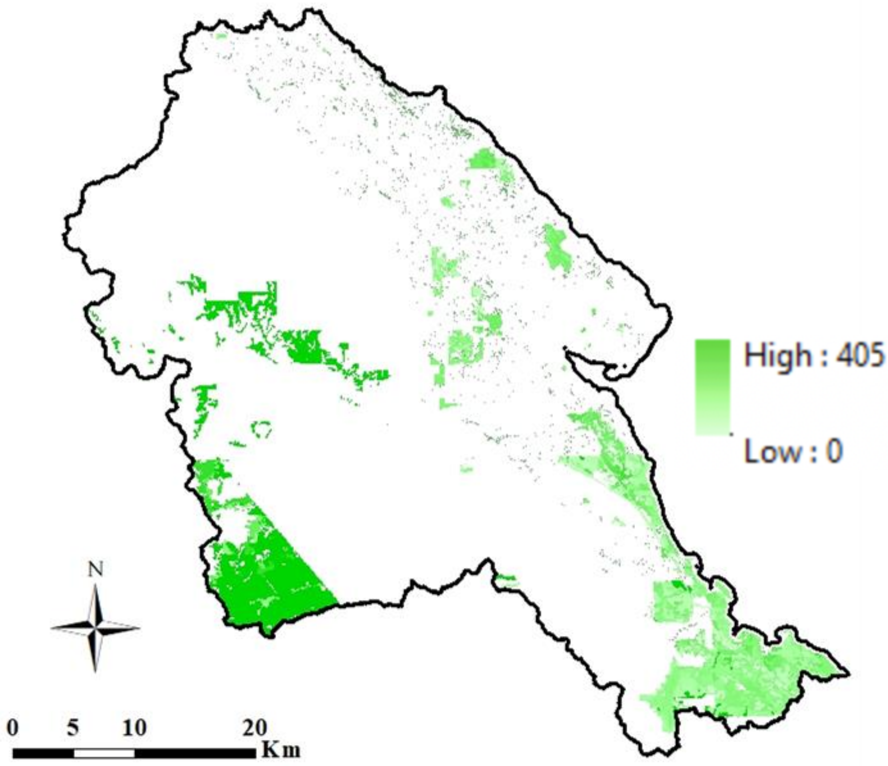

Fig. 6. Vegetation Resources Inventory layer of 2019

Empirical models have been computed by comparing these two age layers. For these, three bio-geo-climatic zones were selected as they are prominent in the study area – CWH-mm, CWH-xm and MH-mm. Empirical models for the CWH-xm and CWH-mm are given below (Fig. 7 and 8). Unfortunately, there was no correlation for the MH-mm zone, which led to manual interpretation. Two broad classes were identified for MH-mm zone – one is young forest (which was logged), and another is old forest.

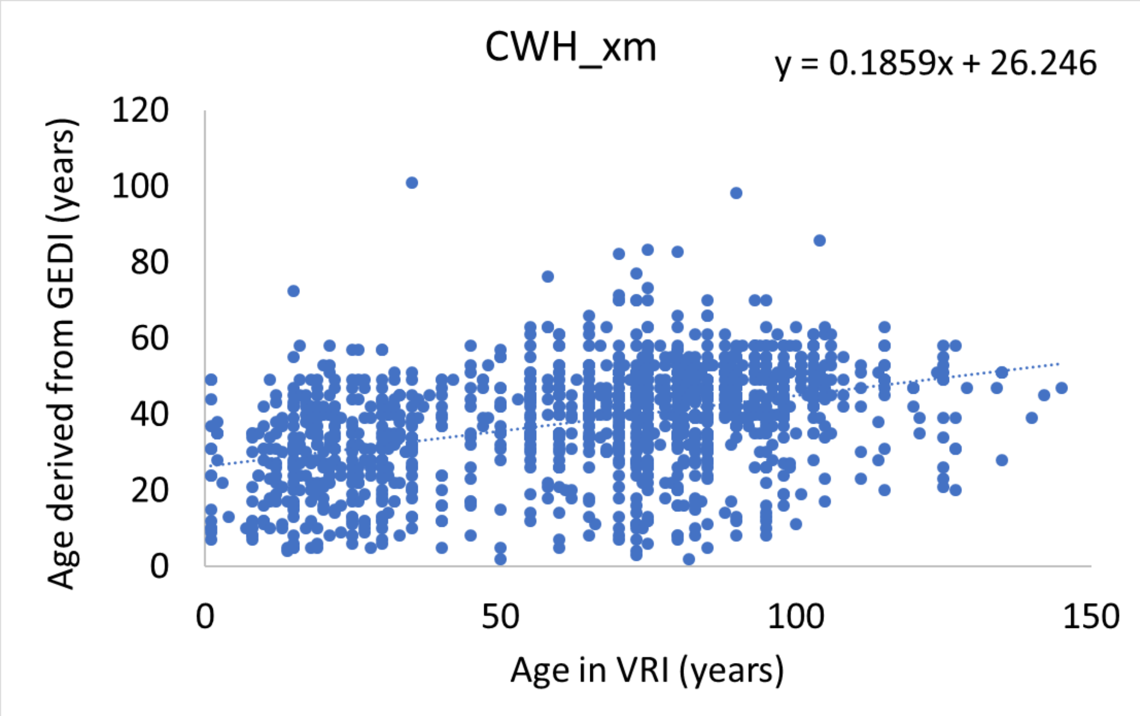

Fig. 7. Empirical model for CWH-xm BEC zone for age calibration

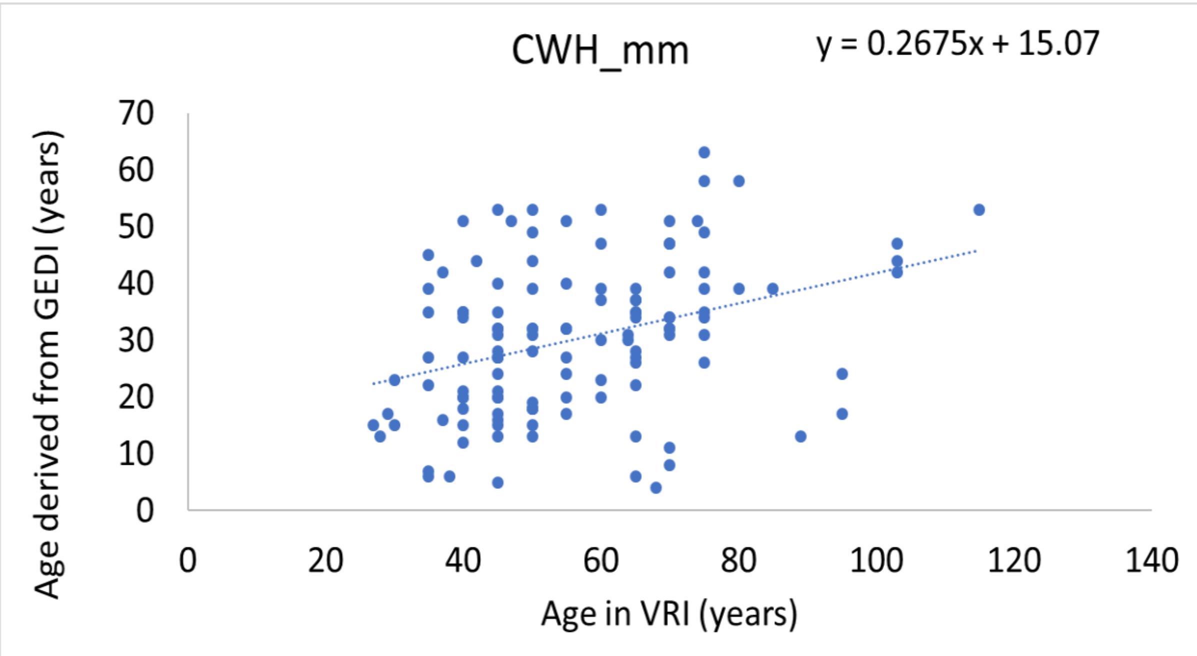

Fig. 8. Empirical model for CWH-mm BEC zone for age calibration

Using the slopes of the empirical models and manually identified forest classes for MH-mm zone, the age raster was modified and updated (Fig. 9).

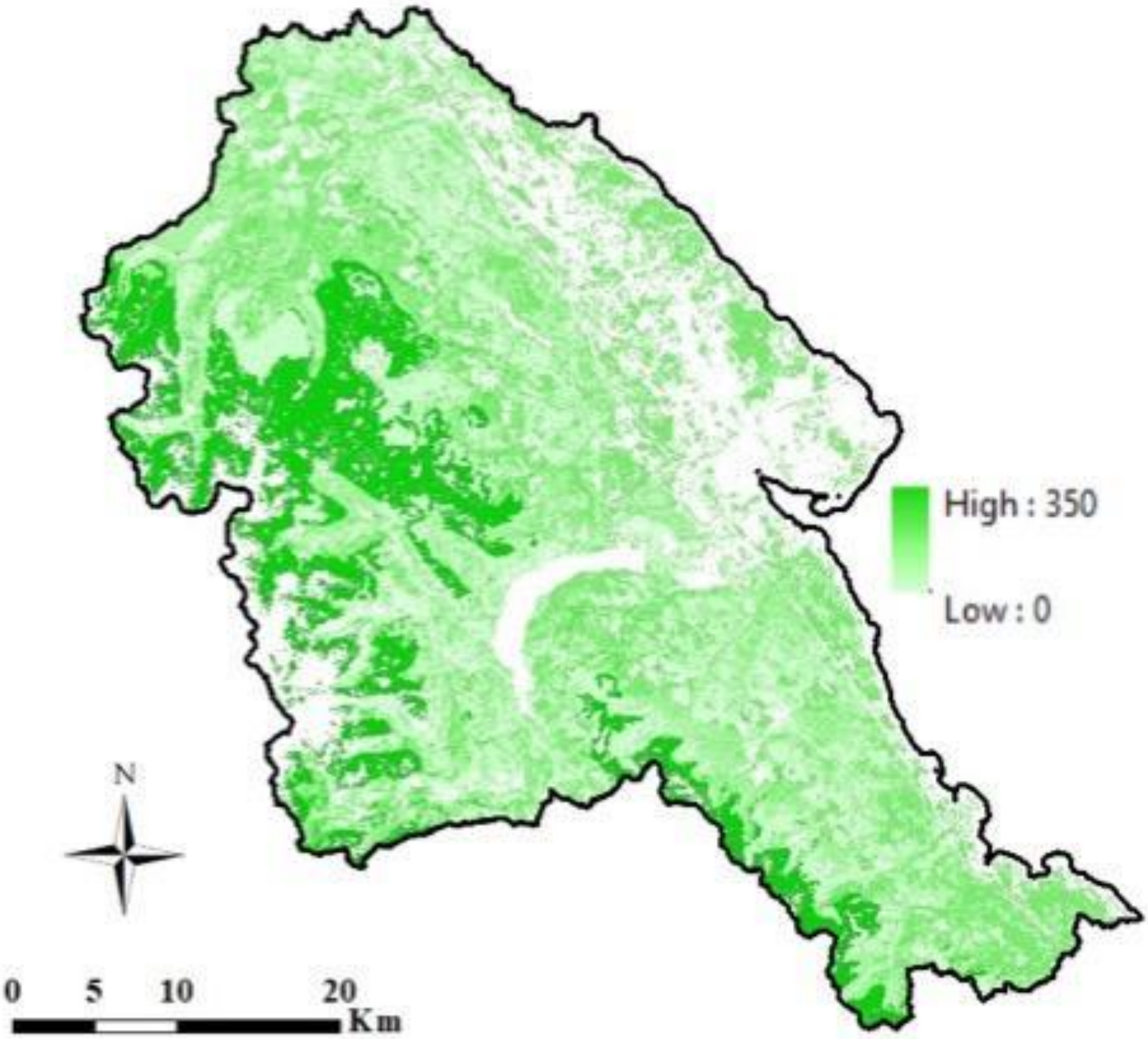

Fig. 9. Modified age raster based on empirical models and manual interpretation

2.6 Identification of Older Second Growth Forest

One of the objectives of this project was to identify some older second-growth forests that are not included in the current SEI polygons. From the modified age raster (Fig. 9), older second-growth forests (60-100) years have been identified in the Nanaimo Lowland area, which are not included in the SEI layer but can be considered for inclusion.

2.7 Updating SEI polygons' attributes

Another objective is to update the SEI polygons' attributes to include the results of carbon and ecosystem modelling. Some new attributes have been added to each SEI polygon (Fig. 10).

- Carbon Storage Value (above ground, soil carbon, and total carbon storage)

- Flow Retention
- Quick Flow
- Sediment Yield

As the model outputs are in raster format (30m resolution), pixel values were extracted for SEI polygons. If there are multiple pixels for any polygon, the average pixel value was considered.

Table

SEI_with_updated_attributes

UPDATE_NO	UPDATE_COM	ATLAS_UPDA	created_us	created_da	last_edite	last_edi_1	DPA	DPA_COMMEN	Shape_Leng	Shape_Area	AG_Carb_ha	Soil_Carb_ha	tot_Carb_ha	FR_sq m	QF_mm_sq_m	SY_ton_sq m
				<Null>	GIS	1/25/2021	No	Not a wetland	2552.974549	144625.372736	163.709434	117.232075	280.941509	0.000949	0.052972	0
				<Null>	GIS	1/25/2021	Yes		593.104416	11298.156129	14.55	155	169.55	0.000085	0.052972	0
				<Null>	GIS	1/25/2021	Yes		567.746105	4827.460945	46	189.4	235.4	0.000505	0.053069	0
				<Null>	GIS	1/25/2021	Yes		1499.685094	42161.789727	57.139535	615	672.139535	0.000397	0.053069	0
				<Null>	GIS	1/25/2021	No	Not a wetland	2194.475312	39363.560509	108.323913	36	144.323913	0.000561	0.052962	0
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				<Null>	GIS	1/25/2021	Yes		283.587223	3131.3451	26.3625	155	181.3625	0	0.053069	0
				<Null>	GIS	1/25/2021	Yes		1471.86929	33319.533375	63.186765	155	218.186765	0.000505	0.053225	0
				<Null>	GIS	1/25/2021	No	Not a wetland	4404.766066	65960.190025	104.464925	36	140.464925	0.000847	1.616667	0
				<Null>	GIS	1/25/2021	Yes		390.408789	4538.180325	83.45	155	238.45	0.000537	0.05291	0
				<Null>	GIS	1/25/2021	Yes		1085.920247	25205.6768	88.855769	155	243.855769	0.000949	0.052974	0
				<Null>	GIS	1/25/2021	Yes		1956.769672	27924.9117	62.836	155	217.836	0.000628	0.052974	0
				<Null>	GIS	1/25/2021	Yes		719.045204	20527.036875	35.913043	155	190.913043	0.000906	1.618889	0
				<Null>	GIS	1/25/2021	Yes		753.093808	30460.749225	29.921875	155	184.921875	0.000711	0.053185	0
				<Null>	GIS	1/25/2021	Yes		622.697278	15257.78925	13.105882	155	168.105882	0.00023	1.613333	0
				<Null>	GIS	1/25/2021	No	Not a wetland	1394.303108	59223.26134	82.572131	36	118.572131	0.000757	1.613333	0
				<Null>	GIS	1/25/2021	No	Not a wetland	1630.402501	74893.98535	44.411111	36	80.411111	0.000887	0.05291	0
				<Null>	GIS	1/25/2021	No	Not a wetland	570.347604	11092.858485	40.8625	36	76.8625	0.000789	0.05291	0.000001
				<Null>	GIS	1/25/2021	No	Not a wetland	757.761133	5061.970229	36.35	36	72.35	0	0.052771	0
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				<Null>	GIS	1/25/2021	No	Not a wetland	6399.728469	133903.609875	88.806855	36	124.806855	0.000392	1.618889	0.000003
				<Null>	GIS	1/25/2021	No	Not a wetland	4753.677854	21062.625204	57.0625	36	93.0625	0.000344	0.031158	0.000068
				<Null>	GIS	1/25/2021	No	Not a wetland	2971.795124	236441.048555	27.448594	36	63.448594	0.000677	1.615556	0.000003
				<Null>	GIS	1/25/2021	No	Not a wetland	507.683827	6322.632325	0	0	0	0	0	0
				<Null>	GIS	1/25/2021	No	Not a wetland	1540.706544	23090.927375	86.053846	36	122.053846	0.000977	1.613333	0
				<Null>	GIS	1/25/2021	Yes		565.835474	16146.658	36.558824	155	191.558824	0.000878	1.018416	0
				<Null>	GIS	1/25/2021	Yes		527.980234	10008.560004	16.369231	155	171.369231	0.000107	1.614444	0
				<Null>	GIS	1/25/2021	Yes		177.795138	407.710415	19.025	155	174.025	0	0.052974	0
				<Null>	GIS	1/25/2021	No	Not a wetland	1090.284515	3609.907898	27.5875	189.4	216.9875	0.001057	1.613333	0.000003

(0 out of 1846 Selected)

Fig. 10. Updated SEI polygons' attribute from the output of carbon and ecosystem modelling

2.8 Estimating carbon storage and carbon storage dynamics

Ecosystems store carbon in their soils, trees (and other vegetation), deadwood, and small dead organic materials, including both above-ground litter and belowground litter. We estimated the carbon storage values for each of these five carbon pools for each LC type and for above-ground and soil carbon pools for each SEI type, using the best of three available methods:

i. Through literature review, we identified the most relevant and reliable carbon storage coefficient that could be generalized across an SEI or LC type.

ii. Using the forest age layer and age-carbon curves, as well as information about the BEC zone we estimated the specific carbon values of individual pixels or SEI polygons.

iii. In GIS, we sampled the aboveground biomass attribute recorded in VRI (where available) within a given SEI or LC type and then used the mean as a generalized coefficient of above-ground carbon storage to assign to locations with the same SEI or LC type where VRI was not available.

We then estimated changes in carbon storage and hence annual carbon sequestration by comparing changes in carbon as indicated by land cover maps for 1984, 1989, 1994, 1999, 2004, 2009, 2014, and 2019.

Estimating carbon storage of land cover types

a) Coniferous and broadleaf land covers

Using the forest age defined at each pixel (forest age layer described in section 2.5) we estimated the carbon pools for each pixel using a forest age-to-carbon curve. This curve represents forest carbon dynamics during post-disturbance and forest regrowth and considerably improves the carbon estimate using a generalized coefficient. The curves were extracted from the Metro Vancouver Carbon storage dataset update report (Greentree, 2019) and originally derived from the forestry simulation model Forecast (Kimmins et al., 1999). The curve we used is for generalized coniferous and deciduous forest types with a site index of 34. This generalized forest type is representative of forests within the Nanaimo Lowlands of the Comox Valley.

b) Non-forest landcover types

We used a generalized approach for estimating the carbon value of non-forest land cover types. First, we diagnosed the ecosystems represented by each land cover type and then used literature review to identify the best carbon coefficients for each LC type based on the ecosystems the LC represents. We assumed the land cover types of water, barren, and snow/ice contain negligible carbon (or carbon that is not labile) and so assigned a value of zero to these pixels. Carbon storage coefficients for the remaining non-forest LC types (wetland, wetland-treed, herbs, shrubs, and mixed wood forest) are summarized in Table 5.

Table 5. Summary of carbon pool values for non-forested land cover types in tonnes carbon/ha (sources are referenced in the text)

lucode	landCover	tot_tree_mass_c	tot_deadwood_c	tot_ag_litter_c	tot_bg_litter_c	tot_soil_c	ecosystem_c
0	no data	0	0	0	0	0	0
20	water	0	0	0	0	0	0
31	snow_ice	0	0	0	0	0	0
33	exposed barren land	0	0	0	0	0	0
50	shrubs	32.43	4.83207	0	6.486	0	43.74807
80	wetlands	74.6	7.5	8.5	9.9	261.8	362.3
81	wetland-treed	123.2	13.2	9.1	15.3	155	315.8
100	herbs	0	0	0	88.2	0	88.2
230	Mixed wood	32.43	4.83207	0	6.486	0	43.74807

c) Carbon storage in wetland-treed land covers and wetland land covers

A diversity of wetland types (e.g., bogs, marshes, fens, and swamps; Ward et al., 1998) are found in the Comox Valley, which have varying capacities to store carbon in their soils and above-ground vegetation. For example, bogs and fens have high accumulations of carbon within their often-deep organic soils but relatively little above-ground vegetation. In contrast, swamps and marshes have primarily mineral soils, which store less carbon, but these wetlands may support relatively large trees and thus have relatively high above-ground carbon storage (Mackenzie & Moran, 2004). Thus, we first analyzed the types of wetlands represented by each of the wetland LC and wetland-treed LC by sampling the mapped SEI wetland types across wetland LC and wetland LC pixels.

Notably, many pixels classified as wetland treed by Hermosilla et al. (2019) did not actually fall within wetlands or riparian areas identified by SEI, suggesting the presence of wetlands never previously mapped in the SEI. These consisted of primarily linear wetlands (likely riparian forests) and relatively isolated pixels and clusters of wetlands.

Of the wetland-treed LC pixels identified by Hermosilla et al. (2019) that did fall within wetlands or riparian SEI, 84.4% were within SEI wetlands and 15.4% were within riparian. The most common were swamp (42.1%), shallow water (19.3%), marsh (12.8%), fenn (6.5%), riparian 1 (6.1%), riparian 5 (6.6%) and lesser amounts of the other riparian classes. Of the wetland (non-treed) pixels identified by Hermosilla et al. (2019) that fell within wetlands or riparian SEI, 99.8% were within wetlands SEI (0.2% within riparian SEI), and of those in wetlands SEI, the most common wetland types were swamp (58.5 %), fenn (27.7%), marsh (11.4%), bog (1.1%) and shallow water (1.1%).

This analysis revealed that wetland and wetland treed land cover classes represent nearly the same thing: a mixture of wetlands, but predominantly swamp and marsh. However, there are some differences. Wetlands (Non-treed) LC have considerably more fenn (27.7%) than the wetland non-treed LC (6.5%), and fenns have high soil carbon values. Thus, we assigned a higher carbon value to the wetland LC, based on the generalized value from SI table 5 in Nahlik and Fennessey (2016), which assumes relatively deep soils of 91cm depth, thus giving it a soil C value of 261.8 tonnes C/ ha. Wetland-Treed LC has a higher prevalence of swamp and marsh and riparian, all of which have lower soil carbon storage compared to fenns. Thus, we assigned the soil C value of 155 tonnes C/ha, which is for a mineral wetland (SI table 2, Nahlik & Fennessey, 2016).

We used the forest height-age-carbon method to estimate the above-ground carbon storage in wetlands LC and wetland-treed LC and used the average value to assign the above-ground carbon value. These values represent the non-soil carbon pools in Table 5.

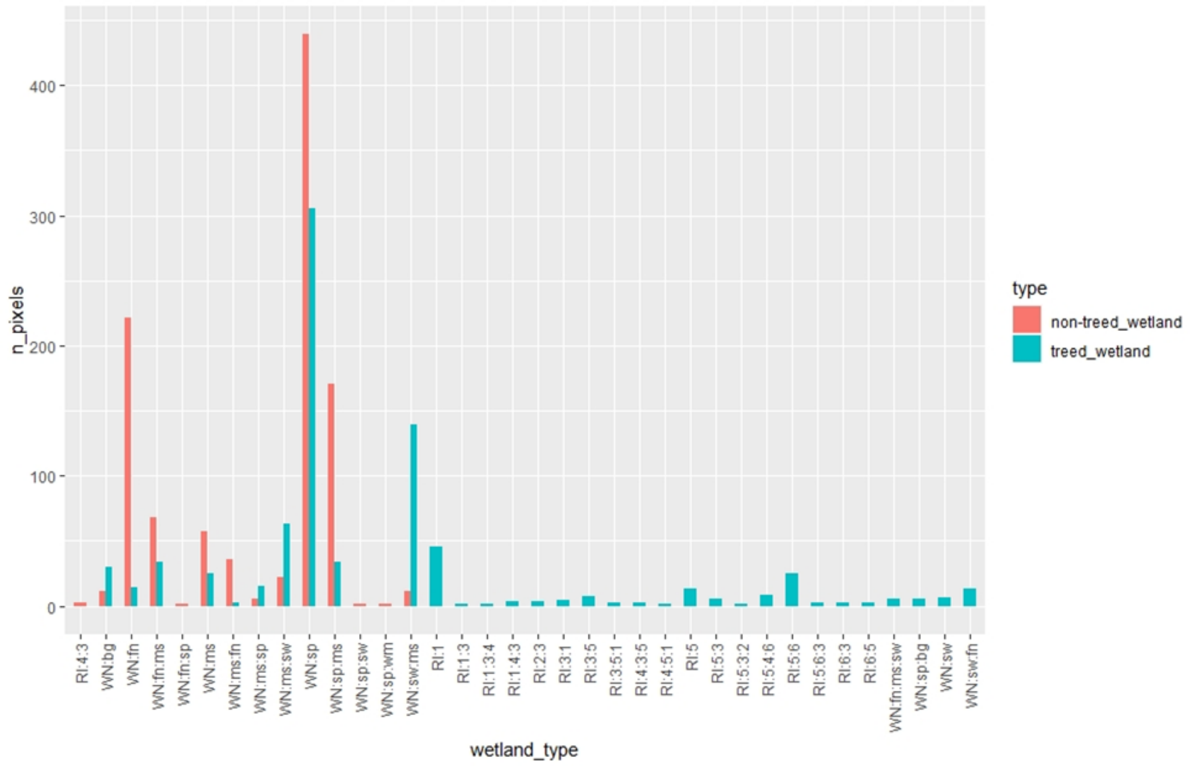


Fig. 11. The frequency of SEI wetland types overlapping wetland and wetland treed pixels

d) Carbon storage in herbs landcover

After reclassifying herbs within the THLB into coniferous, 9.5% of the remaining study area was composed of herbs, which (based on visual comparison with satellite imagery) included primarily grass lawns and gardens and agricultural fields. We assigned a generalized carbon coefficient for these remaining herb landcover pixels. This approach was supported by an analysis of similar landscapes in Metro Vancouver by Paul et al. (2020), which suggested that the soil organic carbon concentration (g/Kg) varies little between annual crops (22.30; sd = 10.20), perennial crops not including cranberry (26.60; sd = 16.10), and grassland (24.60; sd = 21.30). Thus, I took the mean of those three land cover classes and converted them into a generalized carbon storage density using the following steps:

The mean soil carbon concentration g/Kg = 22.30 + 26.60 + 24.60 / 3 = **24.5 g/Kg**

Carbon density (tC/ha) = (mean soil organic carbon Concentration (24.5/100) * Bulk Density (1.2 g/Kg) * Soil Sample Depth (30cm)) * Unit conversion factor (100/1) = 88.2 t C / ha

The bulk density is assumed based on average soils in the region.

e) Carbon storage in shrubs and mixed wood landcover

The literature review returned no representative carbon value estimates for the shrub LC and mixed wood LC. Mixed wood LC outside the THLB represented only .03% of the area and so the carbon values for mixed wood LC were estimated using the same carbon values as the shrubs LC.

Shrubs LC outside the THLB represented 7.6% of the study area and were primarily higher elevation forests with open canopies growing on exposed rocks and cliffs. Carbon was estimated for the shrub LC by sampling the total above-ground tree biomass of representative VRI polygons (n = 8) that corresponded to dense clusters of shrub LC pixels and then using that average of 26.4 tonnes biomass/ha (sd = 21.1). I converted the total tree biomass into the five pools used for other land covers using the following equations from Greentree (2019):

Total tree biomass t/ha = Total above-ground tree biomass (26.4 tonnes / ha) * 1.2 = 31.7

Total Deadwood biomass t/ha = total tree biomass tC/ha * 0.149 = 4.72,

where .149 is a standardized ratio of deadwood to live wood biomass in forests.

Total above ground litter biomass t/ha = Total tree biomass tC/ha * 0.11 = 3.7,

Where 0.11 is a generalized ratio of live tree volume to above-ground litter derived from the height to age tables for conifers

Total soil biomass t/ha = 0,

Where zero is assumed because these forests are essentially growing out of cliffs, and although there is likely some biomass stored in the soil, it is probably quite low. I was unable to find a representative reference in the literature to estimate carbon stored in the soil of this ecosystem type. All biomass values were then multiplied by .5 to equal the total carbon stored in shrubs LC.

Estimating carbon storage for the Sensitive Ecosystem Inventory polygons

There are nine broad classes of sensitive ecosystems, which include: coastal bluff, sparsely vegetated, terrestrial herbaceous, riparian, wetland, woodland, older forest (>100 years), old second-growth forest (60-100 years), and seasonally flooded agricultural fields. We estimated the soil carbon storage of each SEI using a coefficient that was generalized to each SEI class. We estimated the above ground carbon storage for all SEI classes using the methods described above of estimating the height-age-and carbon of each pixel based. To decide which of the two available height-age-carbon curves to use for each pixel (deciduous or coniferous curves), we referred to the landcover map (Hermosilla et al., 2019). For coniferous and shrub LCs, we used the coniferous height-age-carbon curves and for herbs, wetlands, wetland-treed, and deciduous LCs, we used the broadleaf height-age-carbon curves. Once the carbon storage value of each pixel was defined, we then took the mean carbon storage density values within each SEI polygon and assigned that as the above-ground carbon storage density. The soil carbon storage estimates are described below.

Several SEI types were assumed to have very low carbon storage: sparsely vegetated, coastal bluffs, and terrestrial herbaceous. A cursory literature review revealed no suitable estimates to define the carbon storage in these ecosystems. Thus, a low carbon storage density of 10 tonnes C / ha was assigned to these SEIs to recognize that they likely store a small amount of carbon.

Estimating soil carbon storage for SEI wetlands and riparian forests

Wetlands of the Comox Valley Nanaimo Lowlands are classified in the SEI into six primary wetland classes (bog, fen, marsh, swamp, shallow water, wet meadow; Ward et al., 1998). We reviewed the substrates typical of each wetland class as described in Mackenzie and Moran (2004) and used that as a basis to then assign a soil carbon coefficient from Nahlik and Fennessey (2016, refer to SI Table 2 and SI Table 5) that best matched the ecological description (Table 6). Although Nahlik and Fennessey (2016) is based on samples from wetlands in the western United States their estimates are based on extensive data and recognize the large differences among wetland types. Little data was found on carbon contained in wetland types of southwest BC.

Relatively little data was found on soil carbon of riparian forests, which likely varies according to position along the riparian benches (from low to high; Rallings, 2016). A study by Paul et al. (2020) sampled the upper 30cm of soil carbon in forests within a forest agricultural mosaic of the Fraser Valley, which included riparian forests. Their results found a wide range of soil organic carbon densities (g/hg) at the sample site (from 2.00 to 171.90 g/kg). Assuming that the riparian forests have relatively thin or rocky soils, the riparian forests are likely at the lower end of this range, so we assume a value of 10.00 g/Kg, and a bulk density of 1.2 g/cm3, which equals a final soil carbon density coefficient of 36 t C / ha.

Table 6. Linking SEI wetlands classes to an ecological description of the soil and to soil carbon coefficients

SEI Wetland class	**Ecological description of soil** (Mackenzie and Moran 2004)	**Soil Carbon coefficient** (Nahlik and Fennessey 2016; SI table 2 & Si table 5)
WN:bg – Bog	>40 cm deep fibric/mesic peat soils.	615 t C/ha – based on mean of inland organic soil wetlands 0-100cm deep (SI table 2, Nahlik and Fennessey 2016)
WN:fn – Fen	>40 cm deep fibric/mesic peat soils.	615 tC/ha – based on mean of inland organic soil wetlands 0-100cm deep (SI table 2, Nahlik and Fennessey 2016)
WN:ms – Marsh	Substrate is usually mineral, or well-humified peat.	155 tC/ha – based on inland mineral soil wetlands 0-100cm deep (SI table 2, Nahlik and Fennessey 2016)
WN:sp – Swamp	Substrate is usually mineral, or well-humified peat.	155 tC/ha – based on inland mineral soil wetlands 0-100cm deep (SI table 2, Nahlik and Fennessey 2016)
WN:sw - Shallow Water	No info on substrate provided. We assume a generalized class of wetland with 60cm deep soils is a better estimate.	189.4 tC/ha – based on a general wetland type with 60cm deep soils (SI table 5, Nahlik and Fennessey 2016).
WN:wm – Wet Meadow	No info on substrate provided. We assume a generalized class of wetland with 60cm deep soils is a better estimate.	189.4 tC/ha – based on a general wetland type with 60cm deep soils (SI table 5, Nahlik and Fennessey 2016).

Soil carbon storage in seasonally flooded agricultural fields

In the absence of field data, we relied on interpretation from Ward et al. (1998) that seasonally flooded agricultural fields were historically wetlands, and thus we assumed that the soil carbon values would be more similar to wetlands (high carbon storage value) rather than agricultural or grassland LCs (low soil carbon values; Paul et al., 2020). However, soil carbon decreases over time in persistently worked agricultural soils due to agricultural practices such as tillage or fertilizer application. Thus, we assigned a wetland soil carbon value at the low end of options provided by Nahlik and Fennessey (2016; SI Table 5) of 189.4 tC/ha – based on a general wetland type with 60cm deep soils. This may be a low estimate. For example, cranberry fields of the Lower Fraser Valley, which are also seasonally flooded agricultural fields have a far higher soil organic carbon density of 526.50 g/Kg, which is roughly 1090.44 Tonnes C / ha (Paul et al., 2020). Fieldwork to determine soil depth and organic matter density would be required to more accurately assess the soil carbon value of this SEI type.

Carbon storage in SEI forest types

Given that the minimum age of forests to be included in the second-growth forest is 60 years, we assumed most of these polygons are slightly older and assigned the soil carbon coefficient value equivalent to 80-year-old coniferous forests, which is 118.9 t C / ha. In the absence of better knowledge about how old the Garry oak woodlands are, we assumed they are relatively old (e.g., 75 years) and assigned the soil carbon coefficient value equivalent to 75-year-old broadleaf forests, which is 130.9 t C / ha. By definition, the old forest SEI polygons are old coniferous forests, so we assigned the soil carbon coefficient value equivalent to 150-year-old coniferous forests, which is 128.0 t C / ha.

Modelling landscape and carbon storage change

To estimate carbon storage change and net changes in landscape carbon sequestration, we modelled the Comox Valley land covers back in time using land cover maps for 1984, 1989, 1994, 1999, 2004, 2009, 2014, and 2019, and the forest age layer we created for 2019.

There were four steps to the model:

i. Compile land cover maps for each historical era (Hermosilla et al., 2019).

ii. Define a set of rules to back cast forest age from 2019 to the historical LC maps for coniferous and broadleaf pixels.

iii. Assign forest ages where not possible to continuously back cast forest age from 2019.

iv. Estimate carbon storage at each pixel in each time step

The rules we developed to back cast forest age (Table 7) depended on the continuity of forest cover between years and age in the reference LC where reference LC is here defined as the LC map from which a backcast is being made. The target LC is the map for which a forest age is being assigned to. For example, the initial reference LC map was 2019, but once the forest age had been backcasted to the target LC map of 2014, 2014 became the reference LC map for backcasting to 2009, and so forth.

Table 7. Rules for backcasting forest age are based on the landcover pixel change between a target year and a reference year and the ecological interpretation of those changes.

Landcover pixel change (advancing through time)	Ecological interpretation	Backcasting forest age rules
from forest to forest (where reference LC is >= 5 years age)	Continuous forest growth	Target LC age = reference LC age - 5
from forest to forest (where reference LC is < 5years age)	Continuous forest land cover with disturbance implied	Target LC age = assign pre-disturbance age based on strata
From forest to non-forest	Deforestation	Target LC age = assign pre-disturbance age based on strata
From non-forest to forest	Reforestation	No age in target LC because it is non-forest.

For pixels that had been disturbed or deforested we had to estimate the pre-disturbance age. We stratified the 2019 forest ages by three strata (land use as THLB or nonTHLB; BEC subzone; and landcover as conifer or broadleaf) and analyzed the distribution of forest ages to identify the average age, the standard deviation of ages, and plausible rotation age within each stratum (Table 8). The rotation age is the age at which timber is most frequently harvested, which we defined as the 90th percentile of forest ages within the strata. We sampled random numbers from each distribution centred on either the average age (outside the THLB) or rotation age (inside the THLB). We assumed that within the THLB, forestry activities (clear-cutting, road building) were the most common disturbance agent and that harvesting was done typically at rotation age. Outside the THLB, we made no assumptions about how old a forest would have been or what may have disturbed it, so we sampled from the average age. One exception is that we assumed that all coniferous forests disturbed within the CWH-mm had previously been old-growth forests. This is because there is a somewhat limited forestry disturbance prior to the 1970s in much of the CWH-mm areas of the Comox Valley. In these strata, we assigned a pre-disturbance age of 310 years, which was the average age sampled from VRI polygons that correspond to this subzone. This model was constructed in R.

Table 8. Forest age parameters sampled from 2019 data to define normal distributions for generating random pre-disturbance age by land use (within or outside the timber harvesting land base), Bec subzone, and forest type strata.

landUse	BEC subzone	Forest type (landcover)	Average age	Rotation age (90th percentile)	Age (standard deviation)
outside THLB	CWHmm	Coniferous	42	67	18
outside THLB	CWHmm	Broadleaf	20	35	14
outside THLB	CWHxm	Coniferous	46	63	15
outside THLB	CWHxm	Broadleaf	37	68	24
THLB	CWHmm	Coniferous	35	57	19
THLB	CWHmm	Broadleaf	21	39	15
THLB	CWHxm	Coniferous	32	58	19
THLB	CWHxm	Broadleaf	28	51	18

All analyses on carbon storage and backcasting were done using the open-source R programming environment and the packages sn, tidyr, dplyr, stars, sf, zoo, grDevices, ggplot2, and cubelyr.

2.9 Hydrological ecosystem service modelling

Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) is a spatially explicit modelling platform that is free and open source. There are 18 modules available to model and map goods and services from nature to people. InVEST uses maps as inputs and produces maps as outputs. The outputs can be either biological terms or economic values of modelled services.

We used the InVEST modelling platform to map water related ecosystem services in the study area.

We selected seasonal water yield (SWY) and sediment delivery ratio (SDR) to model water quantity and water quality services such as water yield, flood retention capacity and sediment delivery in the Comox Valley. We also considered hydrologic conditions and responses of forest types in the model by reclassifying land cover and forest types based on their canopy coverage and age into different response conditions. Fig. 12 below is the land cover map with forest age delineation in the hydrological models (SWY and SDR).

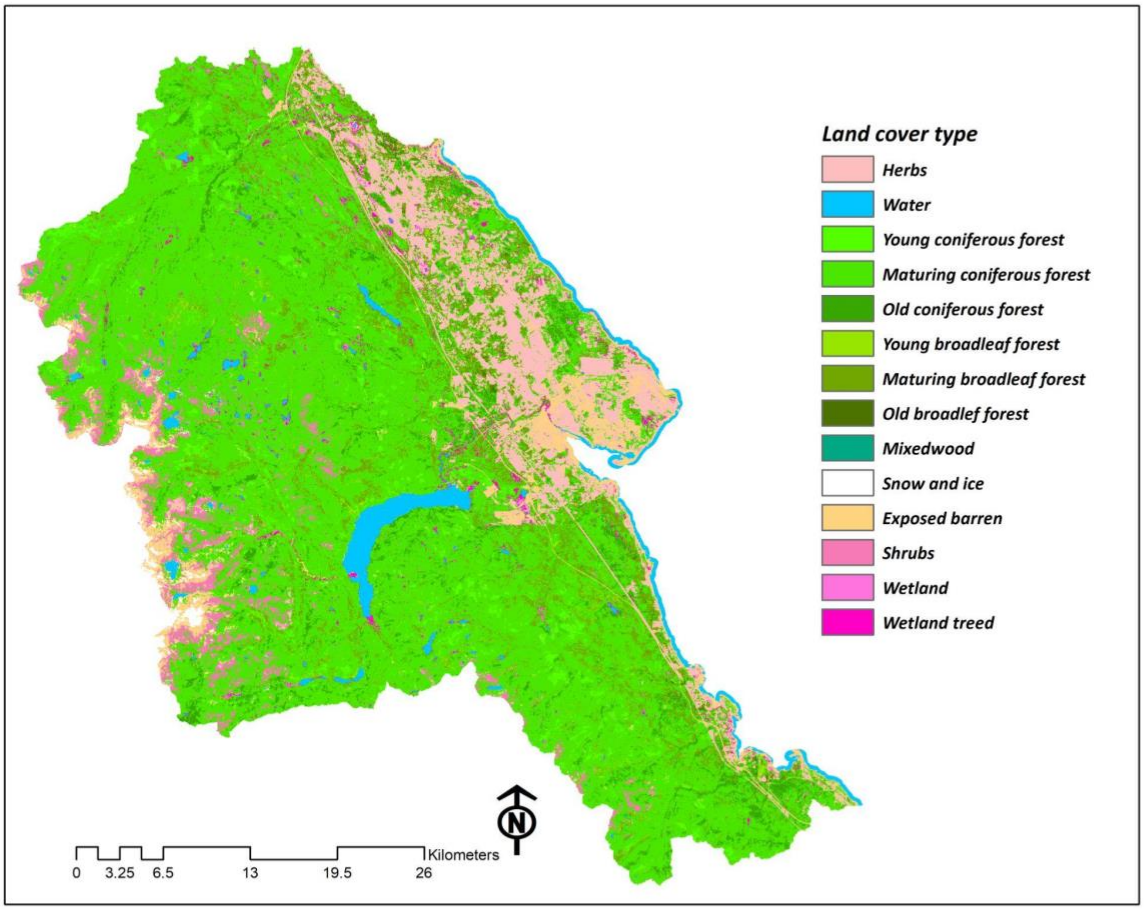


Fig. 12. The land cover map of the study area for hydrological ecosystem service mapping (considering different forest type by age)

InVEST Seasonal Water Yield (SWY) Model

SWY models of InVEST was developed to estimate the spatial quantification of quickflow and baseflow at the watershed scale. The model inputs include monthly precipitation, evapotranspiration, rainfall event in each month, land cover and land use types, digital elevation model (DEM), soil data and a biophysical table. The SWY model is a combination of two hydrological approaches based on the calculation of the net amount of water generated by a pixel after evapotranspiration, and by considering topographic conditions in generating streamflow in a landscape. A full description of the model is provided in the InVEST online user guide (Sharp et al., 2016).

Input parameters for InVEST SWY

Table 9 provides SWY model input parameters and data sources that we derived from different online and publicly available data sources.

Table 9. SWY model input layers and parameters

SWY model input	Dataset source
Precipitation	Climate BC platform https://climatebc.ca/
Reference evapotranspiration	Climate BC platform https://climatebc.ca/
Digital Elevation Model	BC data catalogue https://catalogue.data.gov.bc.ca/
Land use/land cover map	NFIS (https://opendata.nfis.org/mapserver/nfis-change_eng.html) Modified with forest age
Soil group	HYSOGs250m, global gridded hydrologic soil groups (Ross et al. 2018)
Are of interest/watershed	CVCP/ Major watershed boundaries
Biophysical table	Values from a variety of literature sources. Crop coefficients (Kc) primarily from Allen et al. (1998). Curve number (CN) values primarily from NRCS-USDA (2004a).
α, β, γ	Default parameters: (1/12, 1,1)

Monthly precipitation and evapotranspiration data are derived from the ClimateBC platform (https://climatebc.ca/). ClimateBC is a stand-alone window application that uses scale-free data as a baseline to downscale historical and future climate variables. The application uses PRISM climate data and DEM files to generate location-specific climate data. The climate variables for the SWY model are derived from ClimateBC application at the spatial resolution of DEM (25 m).

Sediment Delivery Ratio (SDR)

The sediment delivery ratio model was used to map overland sediment generation and delivery to the stream, which was based on the LUCC data, digital elevation model (DEM), soil erodibility (K), rainfall erosivity index (R), and the biophysical table containing model information. The InVEST SDR model uses a simple approach to provide overland and on-slope deposition of sediments. On a watershed scale, sediment dynamics are a function of climate, topography, soil properties, vegetation, natural hazards such as wildfire and land management practices such as agricultural activities. The SDR model estimates soil loss and sediment export in a watershed. The model is based on the well-known Universal Soil Loss Equation (USLE) to estimate soil loss based on climate, soil properties, topography, and land cover data (Sharp et al., 2016).

The SDR model explores how the transport processes operating at the hillslope scale influence different erosion patterns and spatial variation in soil loss at the landscape scale. As such, it has been used to evaluate land management practices and as a research tool to predict the effectiveness of restoration treatments in controlling erosion and enhancing sediment yield. The SDR model uses DEM to compute annual soil loss at pixel level and then estimates the sediment delivery ratios. SDR is the proportion of soil loss which eventually reaches to stream. The SDR model does not consider in-stream processes for sediment dynamics as the model assumption is once the sediment enters to the streams it ends up at the catchment outlet.

The model modifies the universal soil loss equation (RUSLE) on pixel i for pixel/tons annually.

where

· Ri is rainfall erosivity (units: MJ·mm(ha·hr·yr)−1),

· Ki is soil erodibility (units: ton·ha·hr(MJ·ha·mm)−1),

- LSi is a slope length-gradient factor (unitless)
- Ci is a cover-management factor (unitless)
- and Pi is a support practice factor (Renard et al., 1997).

Table 10. SDR model input layers and parameters

SDR model input	Dataset source
Land use/land cover	NFIS (https://opendata.nfis.org/mapserver/nfis-change_eng.html) Modified with forest age
Digital elevation model	BC data catalogue https://catalogue.data.gov.bc.ca/
Rainfall erosivity	Global rain erosivity (Panagos et al. 2017)
Soil erodibility	International Soil Reference and Information Centre https://www.isric.org/ We used soil data in 0, 5, 15 and 30 cm of different soil types and then integrated for each group. Map of all soil groups is available in appendix B.

3. Results

3.1 Updating Principles, Goals, Objectives

The most important principle identified is connectivity. Other potential top choices for updated principles include restoration, climate adaptation and protection.

The spirit of previous NWB goals remains the same (to conserve and protect ecosystems, especially sensitive ecosystems but not exclusively; restore and regenerate ecosystems and ecological processes; and advocate for community valuing nature, including promoting nature-based solutions), although the framing needs to be updated to reflect the current context.

The main threat to achieving NWB goals in the Comox Valley is development pressure. This is also within municipal government jurisdiction. Other threats, including logging, fall under provincial jurisdiction and NWB may have less capacity to influence these practices and regulations. Other threats identified included barriers to collaboration and a lack of knowledge and expertise.

3.2 Jurisdictional Scan

There are several policy instruments that guide and affect sustainable land use and conservation in Comox Valley. K'ómoks First Nation policy will be covered in a separate section because of the different kinds of the jurisdiction they have in their territory. All other policy instruments will be summarized thematically. Available policy directions are structured by the Local Government Act; governments must therefore ensure that they have the Local Government Act grants authority to write their bylaws in particular ways; some environmental protections are also governed by provincial and federal law.

The primary strategies and tools that are available to local governments to affect sustainable land use include the Regional Growth Strategy, Official Community Plans, Urban Forest Strategies, waste and stormwater bylaws, water conservation bylaws, zoning bylaws, building bylaws, development information approval areas, develop permit areas, development cost charges, and parks and greenway strategies. For a full list of relevant bylaws and strategies that were publicly available on government websites, please see Appendix D: Jurisdictional Scan.

Water Supply and Use

To ensure drinking water quality, CVRD has a Comox Lake Watershed Protection Plan (2016), which includes goals and recommendations to acquire riparian land around Comox Lake and regulate recreational use around the watershed. The Town of Comox and the City of Courtenay receives water from Comox Lake through agreements with the CVRD and therefore do not have their own watershed protection plan. The Village of Cumberland has a Watershed Management Plan (2016) for its drinking water sources (four man-made reservoirs on Cumberland Creek and Allen Lake); risk mitigation actions include an emphasis on trail management and on community engagement (i.e., education). The CVRD also has some residents who receive drinking water from the Oyster River Watershed and an Oyster River Watershed Protection Plan will be developed in the future.

Municipalities regulate resident water use with a goal of conserving water and reducing water consumption. This was established as a priority in CVRD's Regional Growth Strategy and mandated in municipalities through water conservation bylaws primarily focused on reducing water consumption in summer months. Municipalities also set targets for reducing consumption. For example, at the time of Town of Comox's OCP in 2011, resident water consumption was at 428 litres per capita per day (428 l/c/d) (p. 96). This was lower than the 2008 baseline of 600 l/c/d (Objective 2.4.2.1.6), but still higher than what the OCP recognizes as the national average of 327 l/c/d. Bylaws mandating water conservation by regulating and limiting outdoor watering in summer months include: Village of Cumberland Water Conservation Bylaw 807, 2005; CVRD Black Creek/Oyster Bay Water Conservation Bylaw 519, 2018; CVRD Water Conservation Bylaw 129, 2010 (also applies to Courtenay and Comox, last amended in 2022). CVRD further encourages water management through a Smart Water Meter rebate.

Jurisdictions also encourage reducing water use by encouraging drought-resistant landscaping. Town of Comox's OCP encourages "Xeriscaping" which they define as "landscaping and gardening using drought tolerant plants that minimize or eliminate the need for irrigation." City of Courtenay's new OCP under their Building and Landscape Policy, Article (3), "Living landscape elements incorporated for water and energy conservation purposes." The CVRD also includes links to "naturescaping" on their website – which refers to landscaping with drought-resistant species to reduce water use.

Stormwater Management and Retention

Municipalities have bylaws to manage stormwater, connections to storm sewers, and increase runoff and water retention capacities. Master Plans for both storm sewers and sanitary sewers are often created at the same time (although then separated to become two separate plans). Sewer bylaws establish connection costs and regulate and define acceptable contaminant levels. Stormwater bylaws also encourage groundwater retention and, alongside building bylaws, require that water flows maintain a pre-development level. The CVRD, in their 2010 Sustainability Strategy, encourages water retention in Objective 3.7.1: Buildings and sites are designed to manage stormwater in an ecologically sensitive manner ("Ecologically-based developments integrate living systems and landscaping with stormwater management, such as rain gardens or bioswales" (p. 62). Stormwater retention is also encouraged and regulated in the Regional Growth Strategy and in each jurisdiction's Official Community Plan.

Stormwater bylaws may encourage water retention mandating that water should infiltrate ground rather than enter storm sewers. For example, Town of Cumberland Municipal Stormwater System Regulation and Fees Bylaw 1024, 2015 mandates groundwater retention in Article (1) "In an effort to maintain pre-development groundwater flow regimes, stormwater should be infiltrated as close as practicable to the initial source" - overflow of this infiltration system will go into municipal storm water system and Article (2) which encourages rainwater harvesting, but regulates that unused rainwater should be returned to groundwater system. The City of Courtenay aims to reduce sediment in storm sewers through the Storm Drain Connection Fee Amendment Bylaw 2182, 2001, which adds a provision to add oil and grit filters to storm drain connections. This may improve the water quality of storm sewer outputs. The CVRD Sewer Development Cost Charges (which also apply to Comox and Courtenay) specifically specify that they want to encourage development with a “low environmental impact” – but no further detail is supplied.

Building bylaws can also affect water retention by mandating pervious surfaces. Town of Cumberland Building Bylaw 949, 2012, Article 26(ii) "encouraged to provide infrastructure to retain as much stormwater on the site as possible" and Article 26(iii) further regulates water drainage so flow of water does not damage sensitive areas or unduly cause erosion. The City of Courtenay Subdivision and Development Servicing Bylaw 2919, 2018 encourages site adaptive planning and limiting impervious surfaces (but does not require it). This will likely be updated to reflect priorities detailed in the 2022 OCP.

The Town of Comox has recently passed two additional bylaws to regulate soil drainage capacity and runoff: Comox Infrastructure Drainage Protection Bylaw 1824, 2021 and Comox Runoff Control Bylaw 1919, 2021. The Infrastructure Drainage Protection Bylaw clarifies requirements for an Erosion and Sediment Control (ESC) plan and/or a $10,000 security for new developments and when adding or removing soil of at least 1.0m, removing 10+ trees/35% of trees/gradient of the cleared area. The Runoff Control Bylaw maximizes the absorptive capacity of land by regulating and limiting the amount of area that may be covered by impervious surfaces and by requiring soil improvement. Article (5) states that "The percentage of parcel area that is covered with impervious surfaces must not exceed 60% in the case of parcels in residential zones, and 90% in the case of all other parcels" and Article (6) requires replacing topsoil and combining with scarified subsoils to restore the absorptive capacity of soils; see also (9)a.

Coastline and Floodplains

All jurisdictions have established setbacks from normal water levels to avoid flood risk. There are also additional evaluations required when building on a mapped floodplain. Floodplains are often mapped with their own bylaw and included as Development Permit Areas; setbacks are reinforced as required through permit bylaws, zoning bylaws, and building bylaws. Floodplain bylaws include Town of Comox Flood Plain Designation Bylaw 1474, 2006; City of Courtenay Floodplain Management Bylaw 1743, 1994 (and subsequent amendments); and CVRD Floodplain Management Bylaw 600, 2020.

The City of Courtenay and the Comox Valley Regional District are starting to encourage a transition to “Green Shores” and move away from engineered shoreline erosion prevention. The CVRD is part of the pilot Green Shores for Homes Incentive program (funded by the Real Estate Foundation of BC and Pacific Salmon Foundation). As part of this pilot, they are involved in organizing training events for the public and form part of the Green Shores Working Group (since 2017). The Comox Valley Regional District Building Bylaw 142, 2011 (last amended in 2019) refers to shoreline protection in Article 14. Article 14 only refers to engineered shoreline devices and retaining structures (rip rap) with no mention of green infrastructure. The City of Courtenay has also started to promote green shorelines and includes an example report on its website. In Courtenay’s newly adopted OCP, Floodplain objective 2 is to "Respect foreshore sediment and flow processes through the prevention on hard shoreline development solutions and using green approaches that mimic ecosystem functions for erosion protection." They will do so by, for example, specified in Natural Environment Article (10), “Develop shoreline revetment policy to conserve remaining natural shorelines, and restore armoured shoreline with green shores approaches to the maximum extent possible.”

The CVRD (responsible for sanitary wastewater treatment for CVRD electoral areas, K’ómoks First Nation, Courtenay, and Comox) is currently finalizing its Liquid Waste Management Plan. As part of the update, they are also starting the process to relocate the sewer pipes from the coast (construction slated to begin in Spring 2023). This has implications for shoreline management, as the pipes have been protected from wave damage through engineered solutions including rip rap. Once the pipes are relocated, there is an opportunity for re-establishing a more natural coastline.

Other efforts to protect shorelines focus on the erosion control and associated hazards. This motivates bylaws to protect and restore vegetation along shorelines and is also included in the development and building bylaws through Erosion and Sediment Control plans.

Agriculture

There is an interest in maintaining Agriculture Land Reserves as part of a long-term sustainability strategy, to ensure food security (and reduce GHG emissions). Jurisdictions also allow and regulate urban agriculture through bylaws (including mandating minimum lot sizes for chickens and beekeeping). Jurisdictions also regulate, through zoning and development bylaws, buffer, and transitional areas adjacent to agricultural lands.

The CVRD created an Agricultural Plan in 2002, which mapped out soil capacity and existing agricultural practices in the Comox Valley. This plan is now 20 years old. The CVRD has an Agriculture Advisory Committee which evaluates development proposals which affect agricultural lands, this was created through the CVRD Agricultural Advisory Planning Commission Bylaw 453, 2016.

Agriculture is primarily addressed in the Regional Growth Strategy and in Official Community Plans. In OCPs, the priority is to retain agricultural lands. For example, the Town of Comox's Agriculture objectives are - 2.1.9.2. (1) "To protect the agricultural land base and marine foreshore for food production and encourage future growth that is environmentally sustainable; and (2) To protect environmentally sensitive foreshore and estuary areas." In the RGS, the CVRD expressed interest in exploring incentives for the conservation of agricultural land (2C-7) and encourages Environmental Farm Plans (6E2). However, they also note, in MG Policy 2B3 that "In particular, the participation of private landowners in Agricultural Areas within biodiversity corridors should be on a voluntary basis."

Sensitive Ecosystems

All jurisdictions include Sensitive Ecosystem (or Environmentally Sensitive Areas) as part of their required Development Approval Information. The Town of Comox has mapped each sensitive ecosystem as a separate Development Permit Area, while the City of Courtenay has mapped one Environmental Development Permit area which includes several types of SEIs.

SEIs are also excluded from the 5% required park set aside in new developments; this can be seen in the City of Courtenay and the Town of Comox's OCPs, for example. Courtenay will require areas of 4000m2 to be assessed in the chance they contain a smaller Environmentally Sensitive Area that is not currently mapped. Courtenay's new OCP also hopes to "leverage development to pay for new sidewalks and environmental restoration through rezoning amenity charges" (p. 72); they also have a list of "Community Amenity Contributions" which can be negotiated on a case-by-case basis with a developer; some of these may include restoration initiatives.

Green Spaces

There are a significant number of parks in the Comox Valley, of varying sizes. All jurisdictions have expressed that they would like to prioritize environmental conservation as priority consideration for new parkland acquisition. Most parkland is regulated by park use bylaws; these bylaws are generally focused on what is and is not acceptable behaviour in a public park.

Future Park management is further directed by: CVRD's Rural Comox Valley Parks and Greenways Strategic Plan 2011-2030; City of Courtenay's Parks and Recreation Master Plan (2019); Village of Cumberland's Parks and Greenways Master Plan (2014); several Master Plans for individual parks; and the efforts to create a Regional Parks Service.

Private green space is also regulated through nuisance bylaws. Nuisance bylaws regulate private lawn maintenance, including the removal of hazard trees and maintaining safety sightlines around public sidewalks and roads. They may also discourage biodiversity gardens. Nuisance bylaws include:

- CVRD Electoral Areas Unsightly Premises Bylaw 377, 2015 (last amended in 2018) – only nuisance/unsightly bylaw that does not define "unsightly" to include "untended growth";

- City of Courtenay Prevention of Public Nuisances Bylaw 2804, 2014: Article 4."An owner or occupier of real property shall: (i) keep such property clear of noxious weeds, wild grass and other untended growth…"

- Town of Comox Public Nuisance and Property Maintenance Bylaw 1652, 2010: Does not define "unsightly conditions"

- Village of Cumberland Prevention of Public Nuisances Bylaw 870, 2007: Article 3(b) "Every owner or occupier of real property shall: (i) keep such property clear of noxious weeds, and other untended growth" and "unsightly" includes mulch.

Green space is also regulated to combat invasive species. Invasive species are included in some of the nuisance bylaws mentioned above and specifically identified in CVRD's Weed Control Regulation Bylaw 2347, 2001 (last amended in 2005). CVRD also promotes invasive species control by promoting NGOs who partake in invasive species removal on the municipal website; in 2013 the CVRD, the City of Courtenay, the Town of Comox and the Village of Cumberland formed the Comox Valley Invasive Species Partnership.

Urban Forest

All jurisdictions have an interest in increasing tree cover with goals of regulating urban temperatures and secondary goals of potential habitat connectivity. All three urban areas (Courtenay, Comox, and Cumberland) have an Urban Forest Management Strategy. Two of these strategies establish urban tree cover targets (Courtenay: 34-40% Urban Tree Cover by 2050; Cumberland: 30% urban tree cover by 2040); the Town of Comox notes in their 2011 OCP that they are below the recommended 40% tree cover target for municipalities in the Pacific Northwest but do not establish a timeframe to achieve that recommended tree cover target.

Planting trees is regulated in subdivision and development bylaws, but some jurisdictions also have specific tree-cutting and tree-planting bylaws. Bylaws regulate the spacing and species of newly planted trees in subdivisions and new developments. Tree-cutting bylaws mandate permits (generally for trees greater than 20cm in diameter at breast height) and establish charges for replacement costs. Tree-cutting bylaws also help prevent soil erosion in slopes (high gradient areas). The City of Courtenay's Tree cutting bylaw further protects specific native species above 0.5m in height regardless of diameter. Tree Bylaws include City of Courtenay Tree Planting Bylaw 1709, 1993; City of Courtenay Tree Protection and Management Bylaw 2850, 2016; Town of Comox Tree Cutting in Hazardous Areas Bylaw 1066, 1992 (mostly geared towards erosion); and Town of Comox Tree Management and Protection Bylaw 1125, 1994. The Town of Comox tree management bylaw only applies in mapped areas.

Development and Green Infrastructure

In addition to the examples detailed above, new developments are encouraged to lower their environmental impact in different ways, often through building bylaws. Building bylaws encourage low-impact development to reduce GHG emissions (both in terms of material and to conserve water and energy consumption). Often these "green infrastructure" solutions are encouraged, rather than required.

Green Infrastructure is variously defined:

In Town of Comox's OCP: "Green infrastructure can be broadly described as a network of interconnected natural areas, open spaces and corridors that protect and maintain ecological values and functions while providing benefits to people and wildlife" (p. 69). Their environmental policy Article (k) is "Encourage LEED and BuiltGreen (external green certifications) for new developments."

Green infrastructure is defined in Village Cumberland's Bylaw 949, 2012: "Green infrastructure means engineering design that takes a "design with nature" approach, to both mitigate the potential impacts of existing and future development and growth and to provide valuable services. This includes such methods which:

a) promote infiltration and groundwater recharge using disconnected roof leaders, grassy swales and rain gardens;

b) roadside curb cuts that direct road runoff onto grassy sales and rain gardens;

c) reduce runoff and reduce/avoid the impact of peak flows using permeable pavements, rock pits and other catch basins and detention ponds

d) conserve water using low flow fixtures and systems for water reclamation and redistribution

e) utilize alternative energy sources using solar, wind, geothermal, energy; and

f) consist of green building features;"

The definition is refined and more specific in Village of Cumberland's Manufactured Home Park Bylaw 1036, 2016 as: "engineering design that takes a "design with nature" approach, to both mitigate the potential impacts of existing and future development and growth and to provide valuable services. This includes such methods which:

a) promote infiltration and groundwater recharge such as but not limited to disconnected roof leaders, grassy swales and rain gardens;

b) roadside curb cuts that direct road runoff onto grassy swales and rain gardens;

c) reduce runoff and reduce/avoid the impact of peak flows such as permeable pavements, rock pits and other catch basins and detention ponds;

d) conserve water such as low flow fixtures and systems for water reclamation and redistribution such as greywater systems;

e) utilize alternative energy sources such as solar, wind, geothermal, energy;

f) conserve energy by using thermal windows, higher R-ratings in construction, district heat distribution, sewer heat recovery and industrial heat recovery; and

g) green building features such as, but not limited to, green roofs, and green walls."

Each of these Village of Cumberland bylaws encourages the adoption of green infrastructure by explicitly offering incentives: the Manufactured Home Park Bylaw gives 25% rebate at Final Approval for using green infrastructure (article 15(b)) and the Building Bylaw grants 5% discount on permit fees (up to $250) for using green infrastructure (article 14(b)).

The City of Courtenay sets out intentions to encourage green infrastructure in their new OCP. Courtenay's OCP mandates green roofs for buildings of a certain size. The OCP also advocates for prioritizing "Nature-Based Solutions" which is defined as "protecting, restoring and managing natural and semi-natural ecosystems to slow and adapt to climate change" (p. 118). While these priorities will be reflected in upcoming amendments to existing bylaws, the City of Courtenay defines "natural asset" in the Asset Management Bylaw 2981, 2019 as "the stocks of natural resources or ecosystems that have the potential to contribute to service delivery." Other language used includes site-adaptive design and low-impact development.

Climate Change

All four municipalities have pledged to BC's Climate Charter. The Village of Cumberland, the Town of Comox, and the CVRD are climate neutral. The City of Courtenay has not reported any offsets in their municipal GHG emissions. Cumberland and the Regional District purchase carbon offsets to become carbon neutral. The Town of Comox has used waste diversion emissions savings to offset their generated emissions. The City of Courtenay has a climate reserve fund.

Municipal GHG emissions as reported are in Table 11. Some jurisdictions have also calculated and made publicly available per-capita GHG emissions, although these use different reference years. The City of Courtenay per-capita GHG emissions is 2.9 tCO2e/year per capita (baseline 2016). The CVRD electoral areas' per-capita emissions are 4.73 tCO2e/year per capita (baseline 2010). The Town of Comox's per capita emissions are 5.0 tCO2e/year per capita (baseline 2007).

Table 11. Municipal-generated reported GHG emissions (in tCO2e)

	2019	2018	2017	2016	2015
Cumberland	368 tCO2e	317	454 tCO2e	425 tCO2e	176 tCO2e
Comox (Town)	n/a	557.63 tCO2e	n/a	n/a	n/a
Courtenay	1262 tCO2e	1215 tCO2e	1202 tCO2e	1243 tCO2e	1176 tCO2e
CVRD	1993 tCO2e	2171 tCO2e	2003 tCO2e	1919 tCO2e	1792 tCO2e

K'ómoks Policies and Agreements

K'ómoks First Nation (KFN) is at Stage 5 of Treaty negotiations with the federal and provincial governments (Canada and British Columbia, respectively). KFN, through membership in tribal councils, also holds various agreements with the provincial government.

Once the treaty is ratified, K'ómoks will have the right to self-government and their draft constitution will take effect. In their Constitution, the first value listed is "Protecting the lands, waters, and resources that have sustained us.” They further clarify in the preamble, “Through the exercise of our inherent right to self-government, we assume the power to preserve our environment and enhance our identity.” KFN will have the jurisdiction to make laws to protect the environment, they will govern their foreshore areas, and own subsurface rights to areas currently owned by BC and Canada. KFN will govern forests and forest resources (includes timber, salal, mushrooms, etc.), and be able to impose fees for their use. They will have water rights from: Oyster, Puntledge, Trent Rivers and Hart Creek, and will negotiate additional rights for Salmon River. Some areas will be kept in their natural state and be managed as “Tribal Parks”; K’ómoks will govern these lands but will also permit public access.

Until the treaty is ratified, KFN governance decisions are guided by a Comprehensive Community Plan 2014-2024 (CCP), Land Code, Land Acquisition Strategy, and a Cultural Heritage Policy (among others). The CCP relates to land use planning through: establishing setbacks, limiting development in floodplain areas, supporting restoration, and making plans for climate change adaptation and GHG reductions. K’ómoks Land Code, Article 28.1. designates “Sacred Sites and medicinal/ traditional lands to be protected from development or other disturbances.”

The Cultural Heritage Policy is particularly relevant to neighbouring municipalities. This policy is, in part, about “enhancing knowledge of how ancestors took care of lands and waters of territory.” It maps areas of “high archaeological potential” which require a KFN Cultural Heritage Investigation Permit prior to development. The Cultural Heritage Policy also indicates evidence of KFN land use, and suggests some of the ways KFN ancestors took care of the land and waters in the Comox Valley (for example, clam gardens).

It is important to note that KFN also has other policies which are not publicly available. These include a Marine Use Plan (mentioned in the City of Courtenay’s OCP), reports and documents listed in the draft constitution, and other documents and policies not listed.

KFN Agreements

In 2010, CVRD, Courtenay, Comox and Cumberland entered into a Protocol Agreement with KFN with the goal to clarify communication and coordination. The CVRD also has an Indigenous Relations and Reconciliation Assessment Report (2021). This report identifies what other jurisdictions are doing in regard to reconciliation with Indigenous Peoples, and gives an overview of existing policies in the CVRD; this work will not be duplicated here.

KFN is a signatory to several agreements with the BC government through membership in the Nanwakolas Tribal Council. These agreements are available on the BC government website and include: Atmospheric Benefit Sharing, signed in 2016 and valid until 2040 (for carbon credits, although the mapped area is north of the Comox Valley); Forest and Range Consultation and Revenue Sharing Agreement, signed in 2014 and signed and updated in 2021 (one of the objectives is to facilitate the parties obligations to consult and receive consent, although most of the agreement establishes criteria the calculate the percentage of annual forestry royalties KFN will receive); Framework Agreement, originally signed in 2009 and most recently amended in 2019 (establishes an engagement framework – guidelines for level and type of engagement and consultation – for provincial legislation pertaining to member nations' traditional territories and establishes funding cycle to support tribal council); Reconciliation Protocol, signed in 2011 and most recently amended in 2016 (much of the protocol focuses on forestry and forest tenure, as it falls under provincial jurisdiction). KFN is currently a member of the Naut'sa mawt Tribal Council, which they joined in 2018 (according to Naut'sa mawt annual reports).

3.3 Landscape Change

Landcover maps from 1984-2019 show an increase in barren LC up to 2004 possibly associated with the #19 highway expansion in the 1990s, heightened snow/ice LC in 1999 possible the La Niña weather event, and a transition of many coniferous forests into broadleaf forests (Fig. 13). Notably, the transition from coniferous to broadleaf forests has increased the extent of deciduous forests by over 50% since 1984, likely due to conifer forests being disturbed and replaced with early successional deciduous growth.

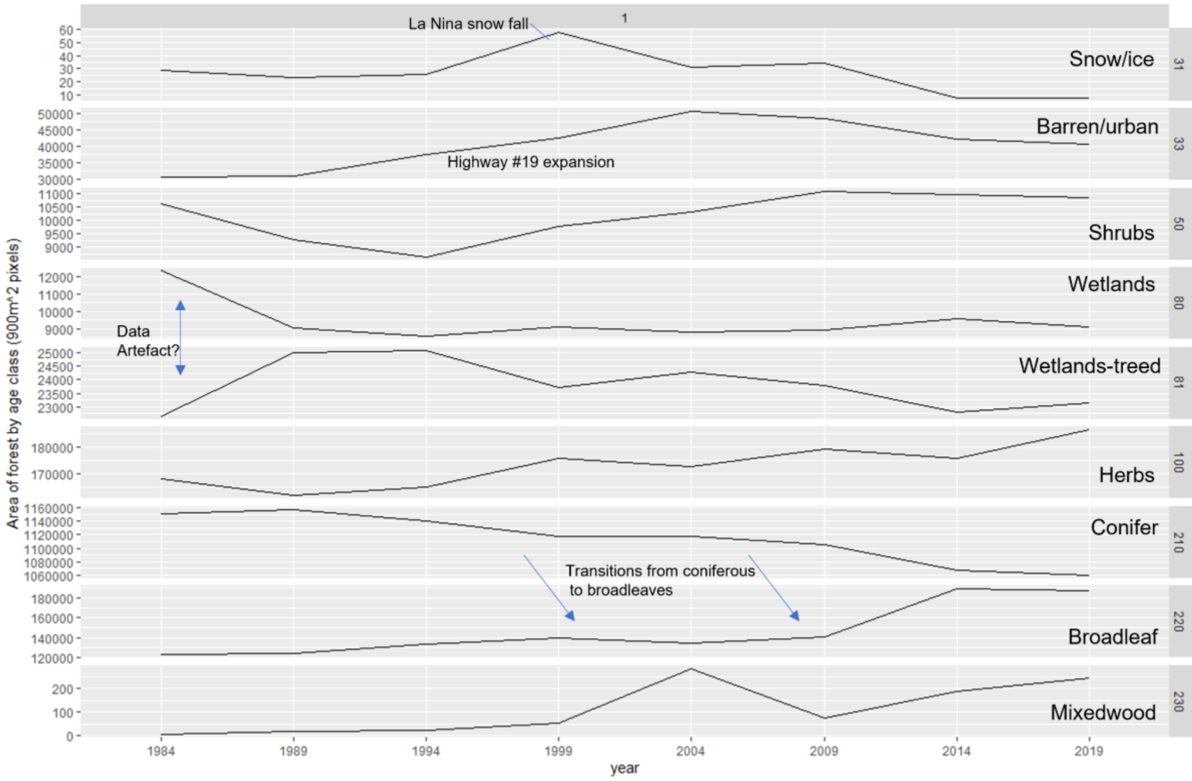


Fig. 13. Changes in the areal extent of each land cover within the Comox Valley 1984-2019 and possible historical drivers.

The backcasting model revealed a general trend of changes in the distribution of forest ages, which include a loss of old-growth forests (forest > 250 years) and maturation of young forests (Fig. 14). Young forests include previously harvested second or third-growth forests that have been transitioning from a highly left-skewed distribution dominated in 1984 by very young forests to more of a normal distribution with a greater proportion of slightly older forests. The extent of old-growth forests has declined by up to 16,283 hectares since 1984 within the CWHmm subzone (41.7% of the entire Comox Valley CWHmm). This estimate assumes that all forests within this zone were old growth prior to disturbance. False detections of disturbance caused by incorrect landcover pixels could also lead to an overestimate. Because the method used to estimate the 2019 age saturates at 125 years, the data does not accurately represent the extent of old growth left in 2019.

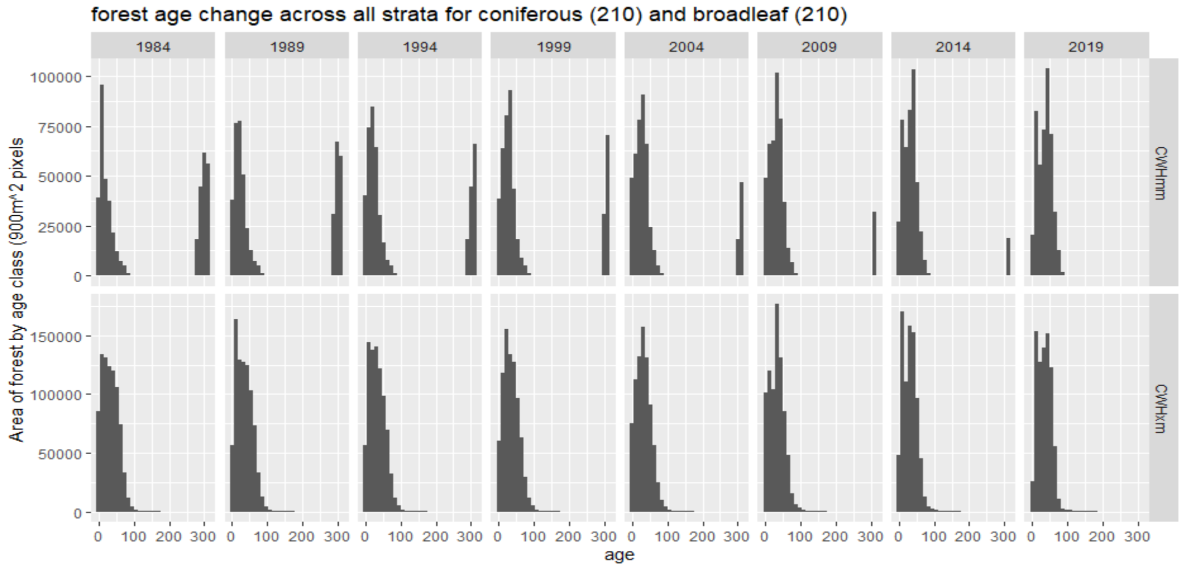


Fig. 14. Distribution of forest ages in the Comox Valley CWHmm and CWHxm subzones as estimated by backcasting forest age from 2019.

3.4 Carbon storage ecosystem services

Carbon storage is spatially heterogenous in the Comox Valley (Fig. 15) and the spatial patterns have changed through time. High carbon storage concentrations were previously found in old-growth forests along the western portion of the valley but as those have been reduced, the highest concentrations are now in recovering second or third-growth forests (Fig. 16).

Carbon storage decreased in the Comox Valley from 1984-2019, resulting in an estimated net reduction of 6.6 million tonnes of Carbon, which constitutes a 27% reduction in carbon storage since 1984. Most of this reduction occurred from 1984 to 2009, after which point carbon storage partially stabilized. Carbon storage may have increased from 2009 to 2014. When compared among administrative / land use boundaries (Fig. 17, Table 12), carbon storage declined most within the timber harvesting land base likely due to forest management. Similar magnitudes of carbon storage loss were observed within some municipalities, especially in Comox and Courtenay, but these declines were concentrated during the early 1990's and have partially stabilized relative to those earlier declines (Fig. 17). In contrast, most provincial parks (the only type of park areas analyzed) had relatively stable carbon storage, except for Wood Mountain Park and Kin Beach Park where carbon storage declined. The only land use where carbon appeared to be steadily increasing was in the region's two Ecological Reserves (Fig. 17).

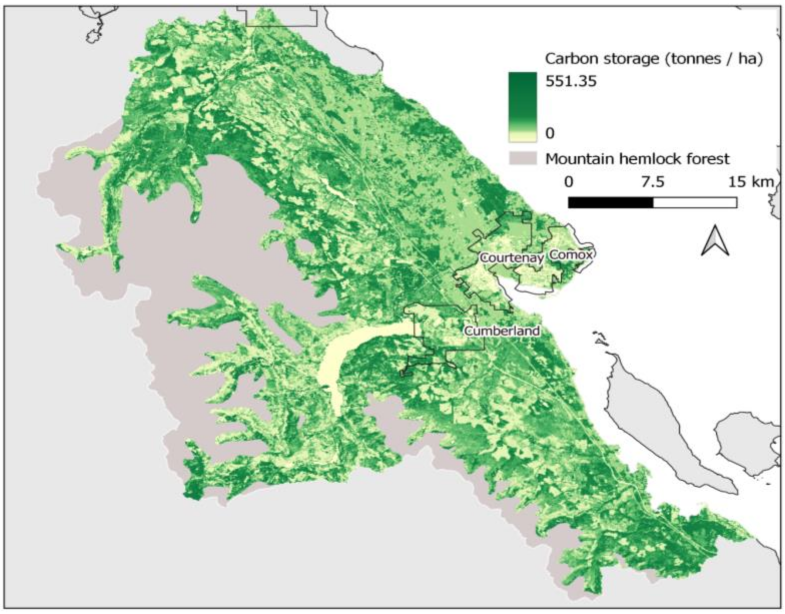


Fig. 15. Ecosystem carbon storage in tonnes carbon/ha

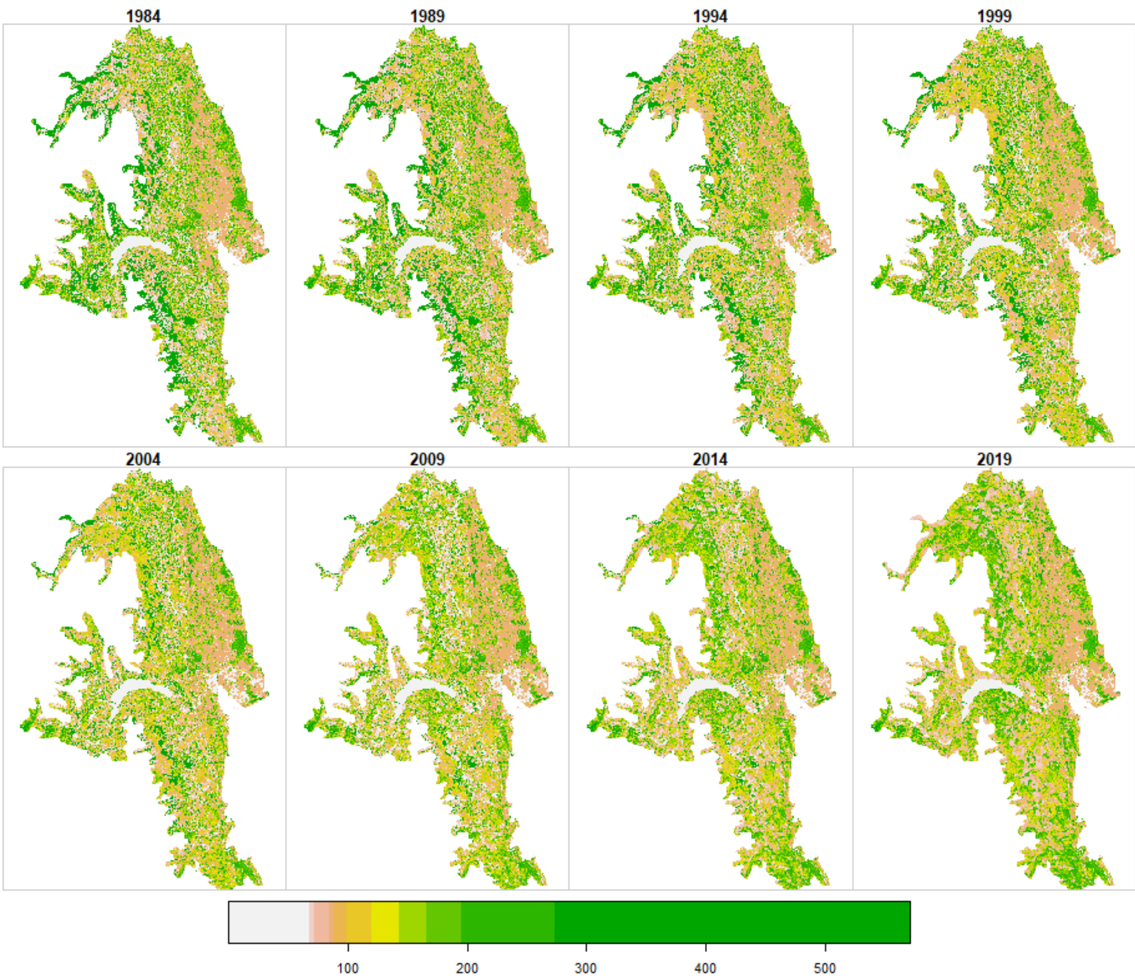


Fig. 16. Changes in ecosystem carbon storage from 1984-2019

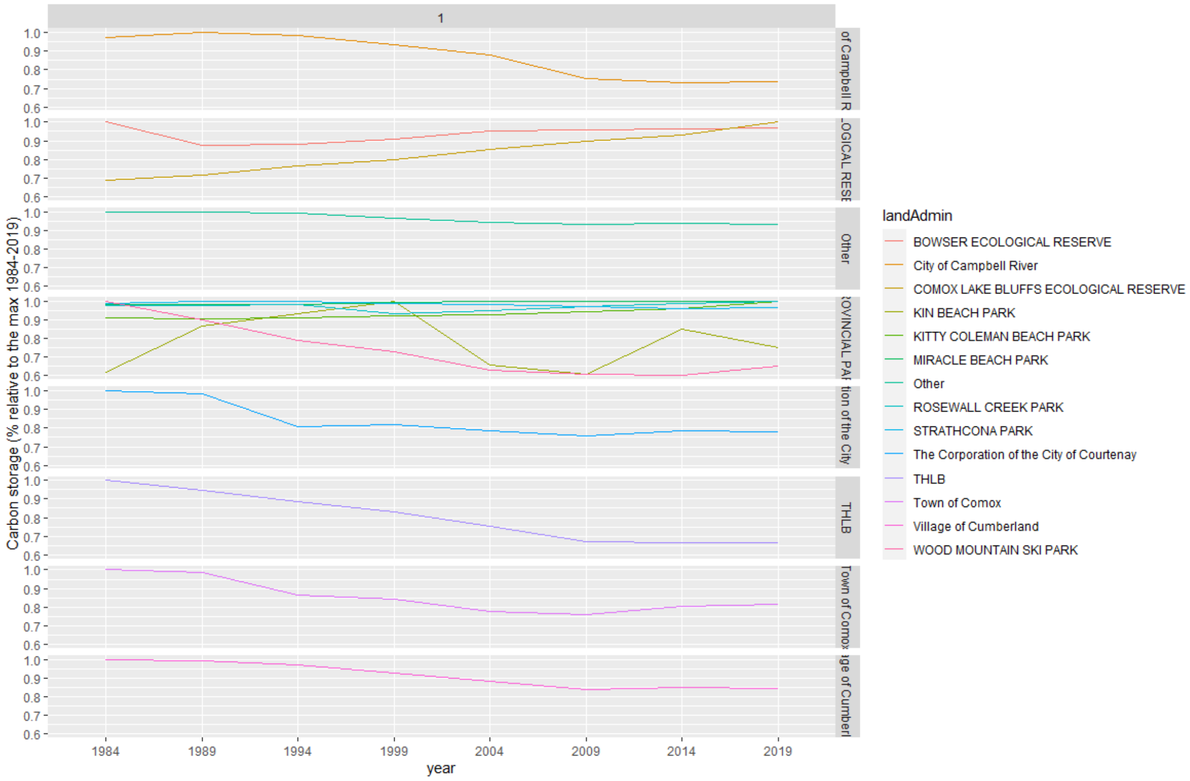


Fig. 17. Changes in carbon storage from 1984-2019 across different land use / administrative units of the Comox Valley

Carbon storage also declined within 'other' land uses, which is the matrix of lands that are neither within parks, municipalities, nor the timber harvesting land base (Fig. 17, Table 12). To better understand the cause of these declines we compared relative losses in the CWHxm and CWHmm subzones. In the CWHxm there was a 10.6% loss in forest area 1984-2019 in the 'other' class, which was likely driven by deforestation caused by agricultural expansion and peri-urban development (both common in the CWHxm subzone). Carbon declined 11.4% in this zone. Meanwhile, there was a 1% net forest increase in the CWHmm, but a 13.4% loss in carbon driven by the transition of conifer forests into broadleaf forests, possibly as related to natural disturbance.

Table 12. Summary of carbon storage changes by administrative unit from 1984-2019

		Total carbon storage (Tonnes Carbon)							
category	**Land administration unit**	**1984**	**1989**	**1994**	**1999**	**2004**	**2009**	**2014**	**2019**
ECOLOGICA L RESERVE	BOWSER ECOLOGICAL RESERVE	24073	21135	21238	21826	22966	23102	23188	23273
ECOLOGICA L RESERVE	COMOX LAKE BLUFFS ECOLOGICAL RESERVE	4873	5064	5419	5632	6016	6323	6588	7063
PROVINCIA L PARK	ROSEWALL CREEK PARK	11658	11628	11734	11134	11337	11582	11789	11923
PROVINCIA L PARK	STRATHCONA PARK	551515	558108	557335	549958	547204	541576	536842	538535
PROVINCIA L PARK	KIN BEACH PARK	226	316	342	366	240	221	311	275
PROVINCIA L PARK	KITTY COLEMAN BEACH PARK	970	966	971	981	990	1006	1021	1066
PROVINCIA L PARK	MIRACLE BEACH PARK	23455	23434	23488	23631	23800	23846	23842	23832
PROVINCIA L PARK	WOOD MOUNTAIN SKI PARK	22817	20544	18078	16637	14425	13930	13793	14824
Town of Comox	Town of Comox	135771	133877	117543	114572	105507	103248	108911	110795
Village of Cumberland	Village of Cumberland	431896	428223	419057	400258	380829	362354	367072	363603
City of Campbell River	City of Campbell River	55643	57335	56310	53704	50583	43315	41852	42078
The Corporation of the City of Courtenay	The Corporation of the City of Courtenay	339605	333346	273449	277384	267312	258162	267063	265427
THLB	THLB	178029 58	1689473 7	157793 26	147953 44	133898 52	119449 10	118706 15	118386 34
Other	Other	507829 2	5101426	504867 5	491163 6	481772 3	474161 9	477680 7	475775 0

		Total carbon storage (Tonnes Carbon)							
category	**Land administration unit**	**1984**	**1989**	**1994**	**1999**	**2004**	**2009**	**2014**	**2019**
Total		**24483751**	**23590140**	**22332966**	**21183063**	**19638784**	**18075193**	**18049694**	**17999078**
Percent reduction from previous time step		**NA**	**3.6**	**5.3**	**5.1**	**7.3**	**8.0**	**0.1**	**0.3**
Percent reduction from maximum observed		**o**	**3.6**	**8.8**	**13.5**	**19.8**	**26.2**	**26.3**	**26.5**

Changes over time in carbon storage represent an indicator of aggregate carbon sequestration and reveal that landscapes of the Comox Valley have been a net emitter of carbon dioxide since 1984 (i.e., more CO_2 is emitted from the landscape than is absorbed) (Fig. 18). However, CO_2 fluxes are highly dynamic. From 2009 to 2014, the landscapes of the Comox Valley began to switch from being a net emitter of CO_2 to being a net absorber of CO_2, and the carbon dynamics have been close to net zero since. This switch is possibly related to changing land management and a slowdown in forest harvesting and development following the 2008 recession.

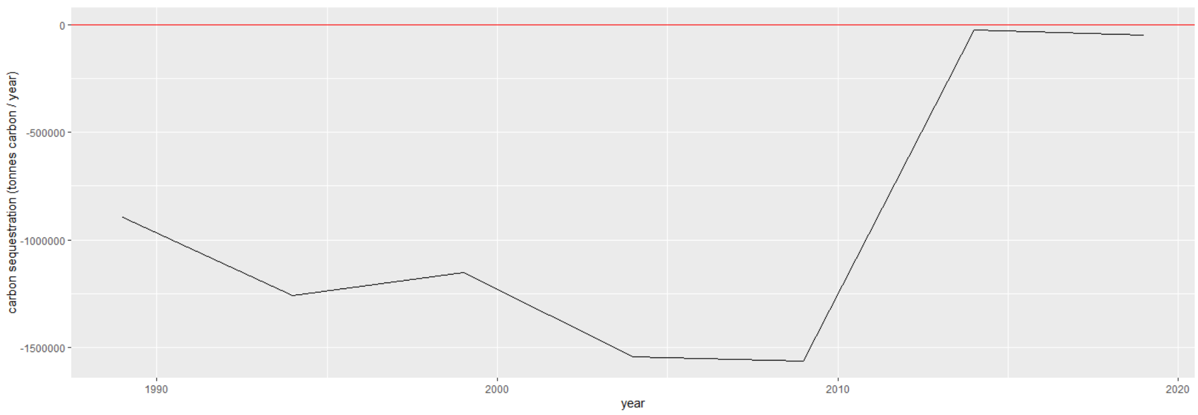
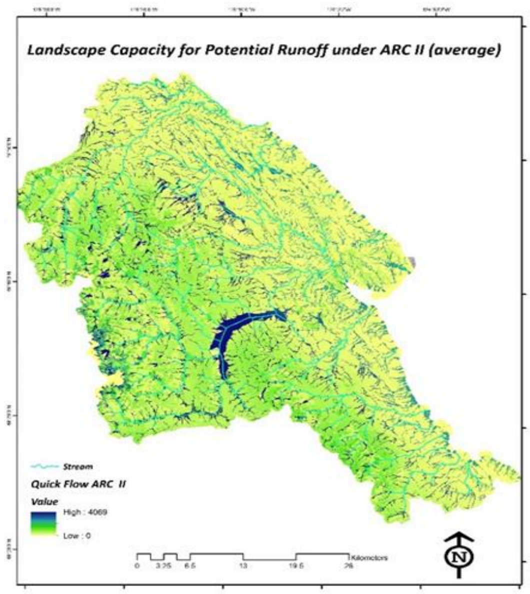


Fig. 18. Net carbon sequestration of the Comox Valley 1984-2019 based on the differences in carbon storage over time

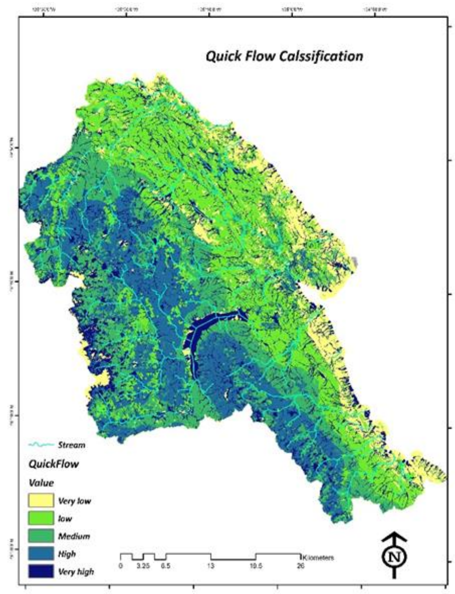
3.5 Hydrological Ecosystem Services

Annual and Seasonal Quickflow

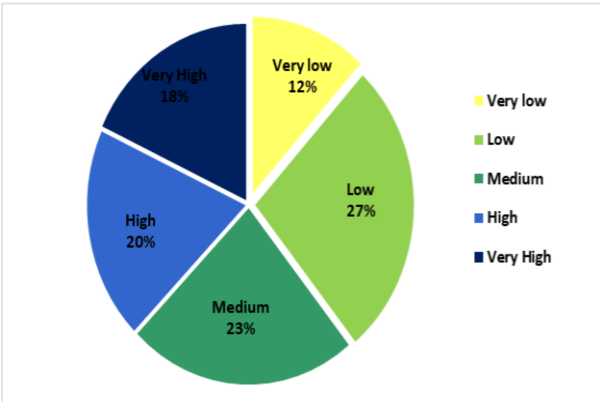
Quickflow is the main indicator for representing runoff in the landscape and the first output parameter of the InVEST SWY model. The amount of water that flows and runoff is known as quickflow. According to the model output as shown in Fig. 19 the annual amount of quick flow varies from 0 to 4069 mm/pixel with the mean value of 398.77/pixel. Using a quantile-based classification approach the quickflow maps are classified into five main categories. Quantiles produce the most heterogeneous map. Seasonal variability of quickflow in the study area is significant from the wet season (December, January, and February as well as early spring in March and April) to the dry season in the summer. As shown in Fig. 19 the highest monthly quickflow was observed in November with the highest value of 697 mm/pixel and the lowest quickflow range among months belongs to July with the highest value of 68mm/pixel.



a) Annual quick flow in the study area for the average antecedent runoff condition (ACR II)



b) Quickflow classification using quantile-based approach



c) Spatial distribution of quickflow classes in the study area

Fig. 19. Landscape capacity for potential runoff and spatial distribution of quickflow in the Comox Valley. Panel a illustrate total quickflow in the landscape which is a proxy for land surface water in the study area. Panel b is the classification of quickfow and panel c is the spatial distribution of each class in the landscape.

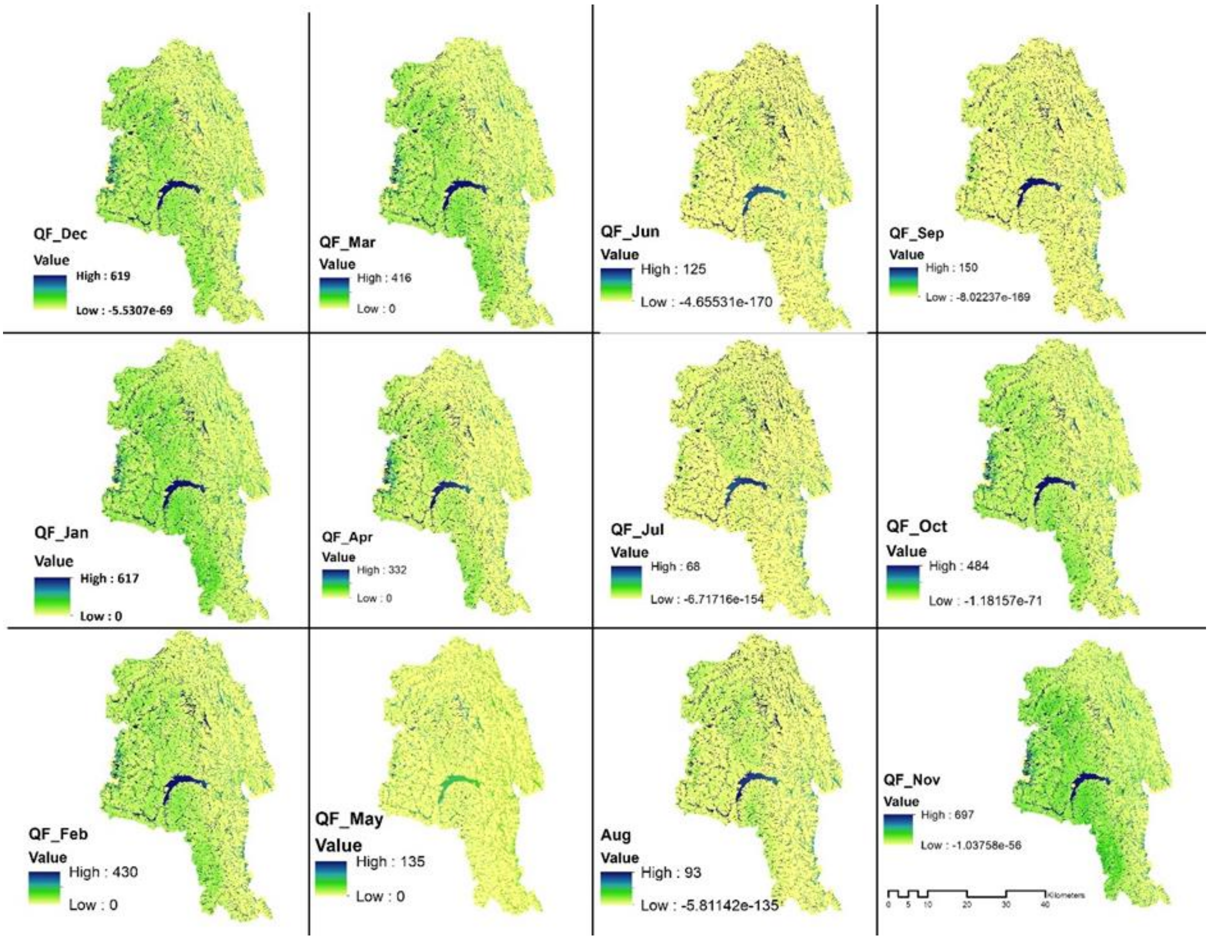


Fig. 20. Quickflow monthly distribution. Seasonal variability between wet and dry seasons is represented in the chart with higher runoff during the winter and dry season in summer.

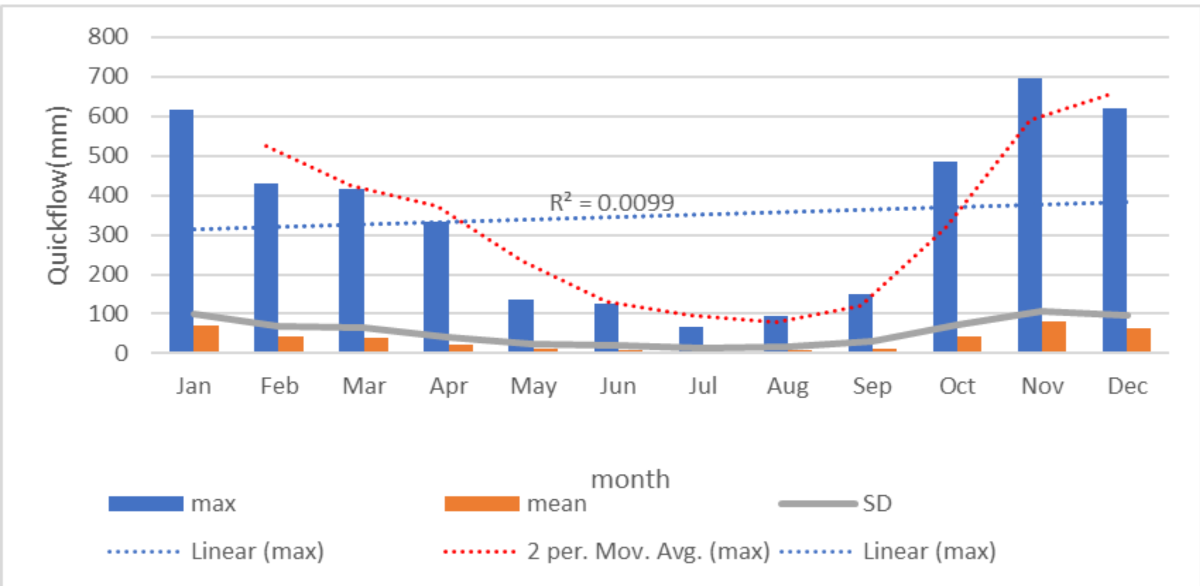


Fig. 21. Quickflow monthly distribution. Seasonal variability between wet and dry season is represented in the chart with higher runoff during the winter and dry season in summer.

Local Recharge

The annual local recharge of the study area is between -730 and 4131 mm/pixel (Fig. 22). Down slopes of the landscape where the elevation is low and close to the ocean have a negative value of local recharge. As shown in the figure recharge rates vary with location due to precipitation patterns. Negative values of the local recharge index in the model mean that those areas do not receive enough of their own water to satisfy their vegetation requirement which is determined by a crop coefficient (Kc) in the biophysical table. According to the spatial distribution of precipitation and evapotranspiration, on the east side of the landscape where the climate is dry maritime recharge rates are extremely low.

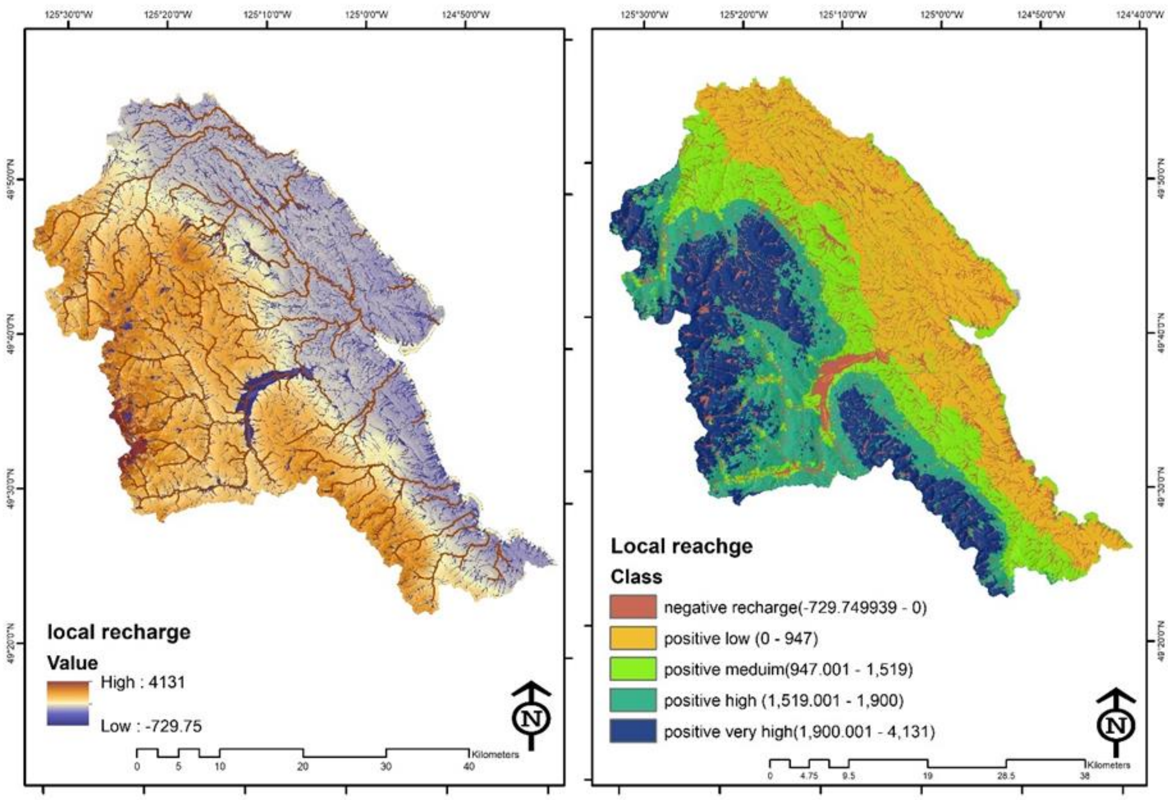


Fig. 22. Spatial representation of local recharge in the study area

As mentioned in the methodology based on the model algorithm to estimate the different variables, it is based on landscape structure, climate condition and soil complexes of the landscape. Therefore, land cover is the crucial input layer into the model, and the final products heavily rely on the land cover types and assigned coefficients.

Fig. 23 represents all the other important variables of the model including a map of curve numbers, actual evapotranspiration (AET), baseflow, map of Lsum (contribution of upslope pixels for runoff), recharge contribution of each pixel to total recharge and mean relative value of local recharge. As shown in the figure the maximum AET is 729.75 mm/pixel annually and the highest values are associated with waterbodies in the landscape. Not surprisingly, the lowest amount of AET is distributed in the higher elevations of the landscape. In general, the spatial pattern of the pixel-based contribution of variables (baseflow, L_sum and Vri) is based on topography and slope gradient.

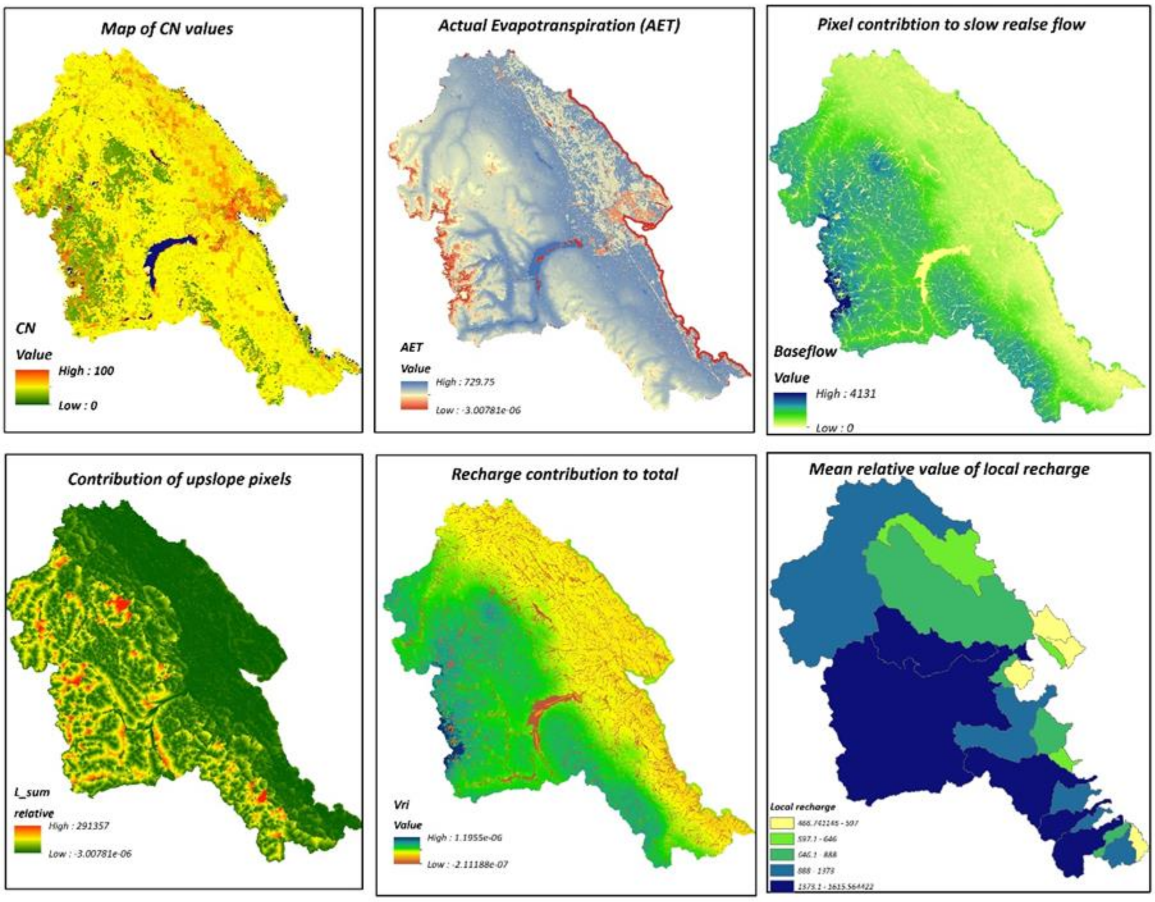
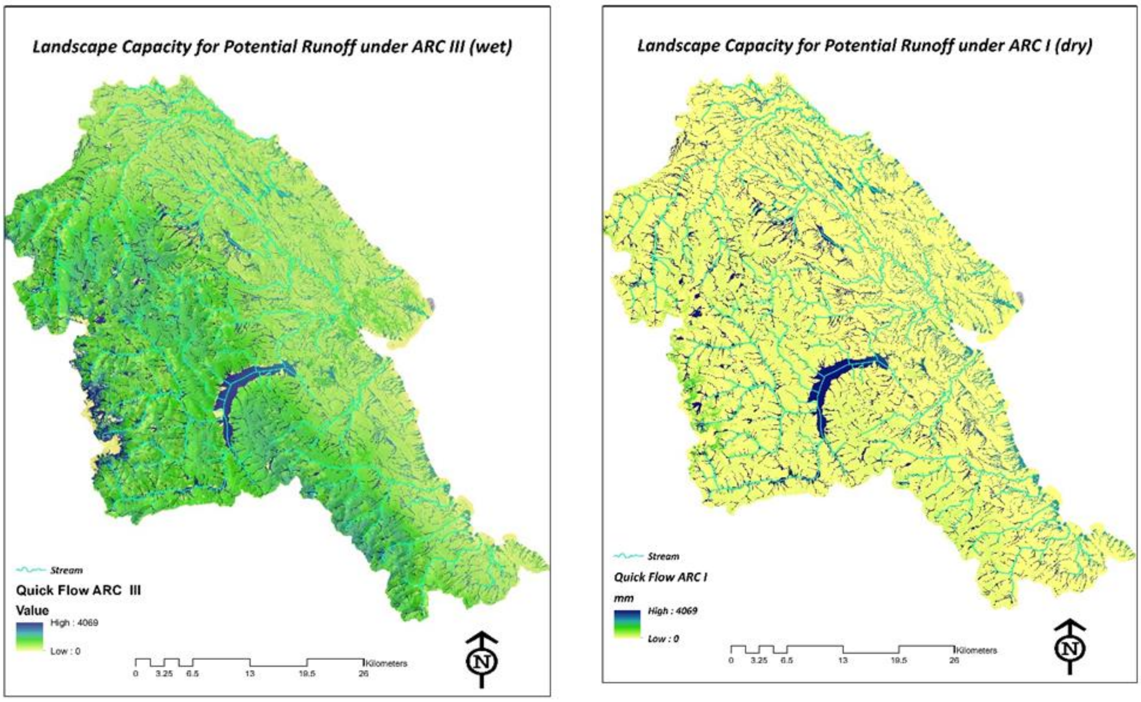


Fig. 23. All other SWY model outputs

Wet/Dry Antecedent Runoff Condition

As mentioned, runoff in the model is based on the curve number approach. Curve numbers for each soil complex and land cover type vary between antecedent moisture conditions. The following maps in Fig. 24 demonstrate the capacity of the landscape in producing runoff for wet and dry moisture conditions. Under ARC dry conditions the capacity of the landscape is highly related to the stream pattern and can be found in higher elevations where precipitation is high, and evapotranspiration is low.



a) Quickflow and runoff potential under ARC wet condition

b) Quickflow and runoff potential under ARC dry condition

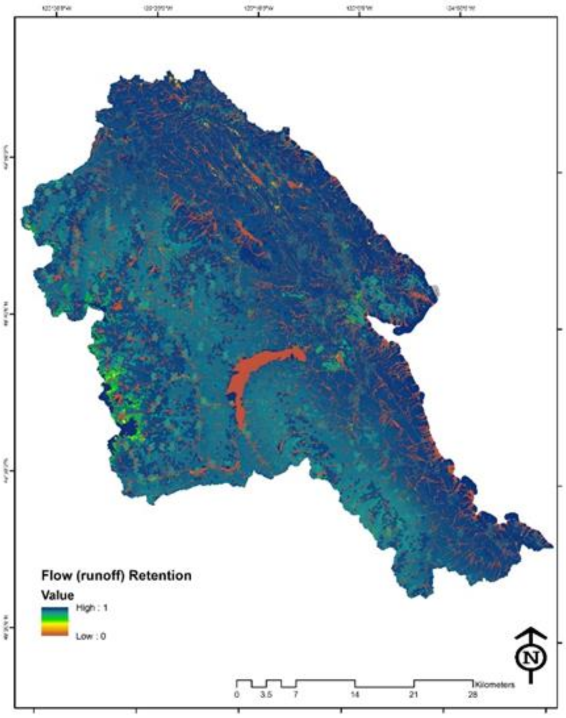
Fig. 24. The capacity of landscape in producing runoff for wet and dry moisture conditions

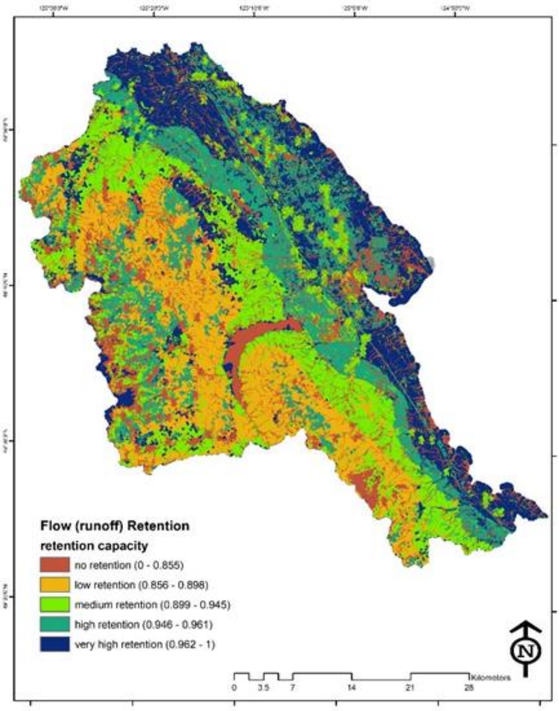
Inland Flood Risk Reduction by postprocessing of annual quickflow index

To assess flood risk reduction, we computed a non-dimensional flow retention index (Mandle et al. 2017) on each pixel as flows:

$$\text{Flow (runoff) retention} = 1 - QF/P$$

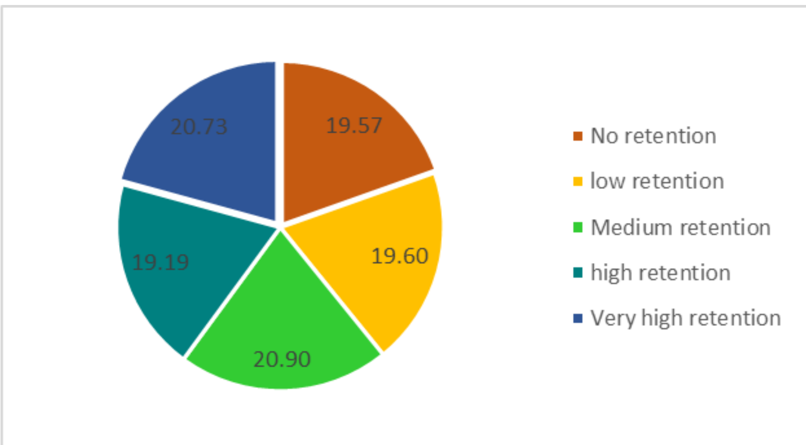
Where QF is the annual quickflow and P is the total precipitation over the year. The index ranges between 0 and 1. A value of 0 indicates that there is no retention by a pixel, and a value of 1 indicates a total retention capacity. Forest act as sponges (retaining runoff) to mitigate flood risk during the wet season. And supplying crucial drinking water, agricultural usage, and tourist activities in the dry season.





a) Flow (runoff) retention

b) Runoff retention capacity in the study area



c) Percentage distribution of retention capacity in the study area

Fig. 25. Runoff retention capacity of the landscape (panel a), classification of runoff retention capacity in the landscape (panel b) and percentage distribution of runoff retention classes (panel c)

Sediment Delivery Ratio (SDR)

The SDR model output is represented in Fig. 26. The maximum potential soil loss is 1250 tons/pixel, and the spatial distribution of this indicator shows that it is highly associated with topography and precipitation, where rainfall erosivity is intense in higher elevations (panel A, Fig. 26). The RKLS indicator is also potential soil loss equivalent to bare soil. In other words, it reflects the potential soil loss per pixel in the original land cover without vegetation cover and proper land management (panel B, Fig. 26). In addition to the soil loss indices, the SDR model produces sediment retention and sediment export, panels C and D, respectively. However, the sediment retention index is not recommended to take into consideration as it converts all land cover classes to bare ground.

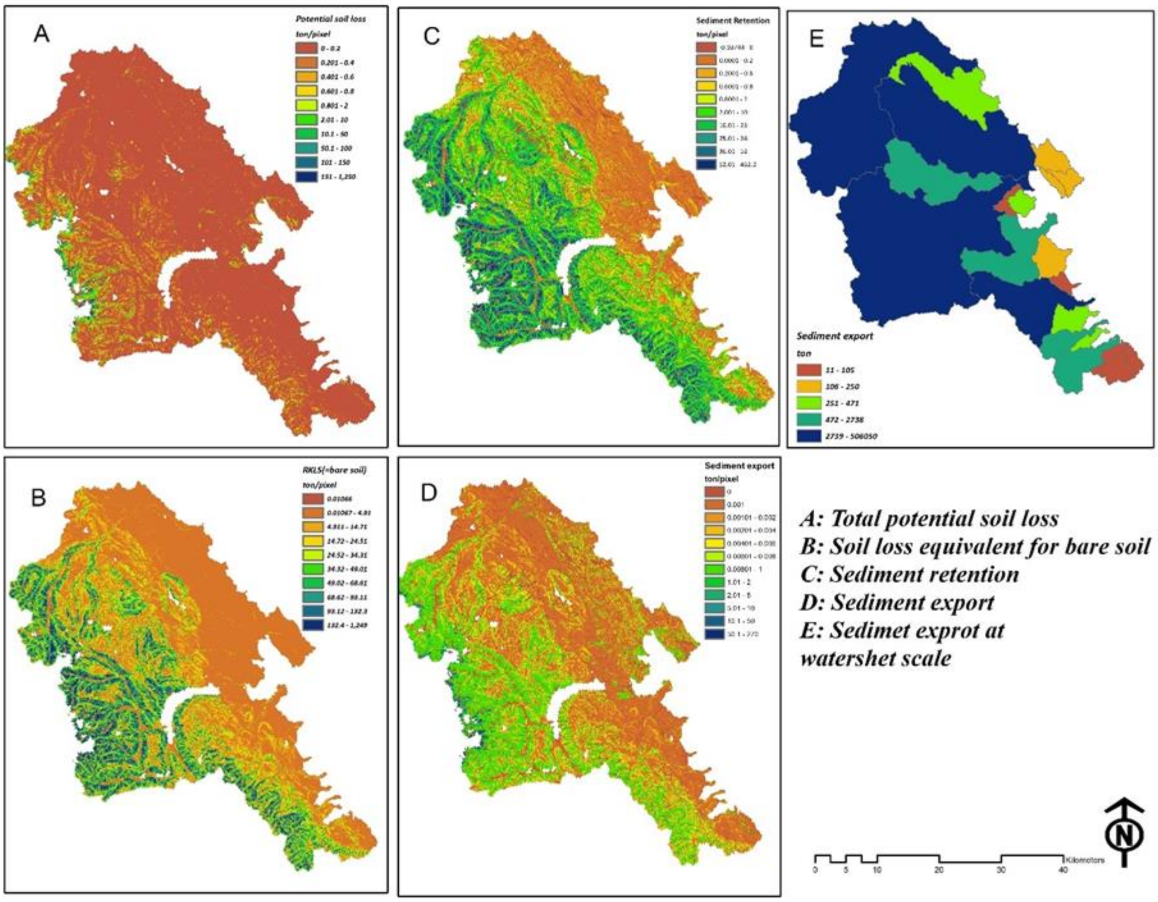


Fig. 26. Soil erosion rate, sediment retention and sediment export in the study area

Sediment Export (Sediment yield)

The sediment yield from a given pixel is a direct function of the soil loss and SDR factor annually in ton/ha. Fig. 27 is provided to understand better the spatial pattern of sediment delivery in the study area. Similar to the previous indices, sediment yield is associated with the geomorphology, topography and soil erodibility (K factor) of terrain. As shown in the figure below, the highest sediment yield is in higher elevations, with high precipitation.

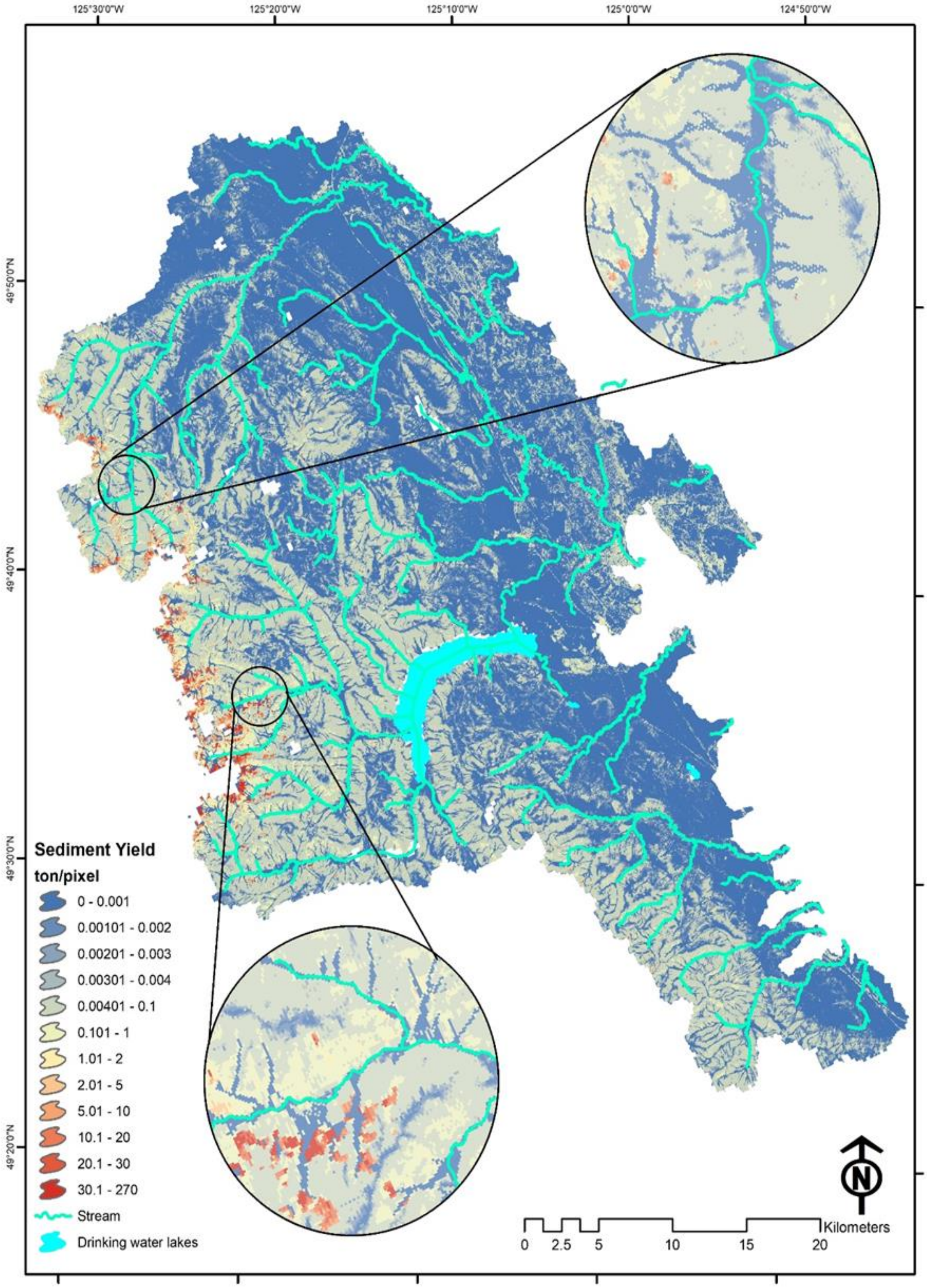


Fig. 27. Sediment export in tons/pixel in the Comox Valley

Linking ecosystem service mapping with SEI polygons

To analyze the spatial pattern of sediment yield from the SDR model in sensitive ecosystems in the study area, we selected riparian zones (RI) and wetland (WN) from SEI vector files and then extracted the statistics of sediment yield data for each specific location of sensitive ecosystems.

Sediment Yield in Riparian Zone and Wetlands

Sediment yield in sensitive riparian zones in most parts of the landscape is negligible. However, areas close to the Tsolum river in the central east part of the landscape are associated with high sediment (3.9 -11.8 tone/pixel). Northern area of the landscape is also identified in the high sediment delivery in the riparian zone of the Oyster River. Sediment yield in wetlands is also of great importance for water quality and habitat inside the wetlands. As shown in Fig. 28, the high concentration of sediment yield is found in those wetlands located in the central part of the study area, just below Comox Lake.

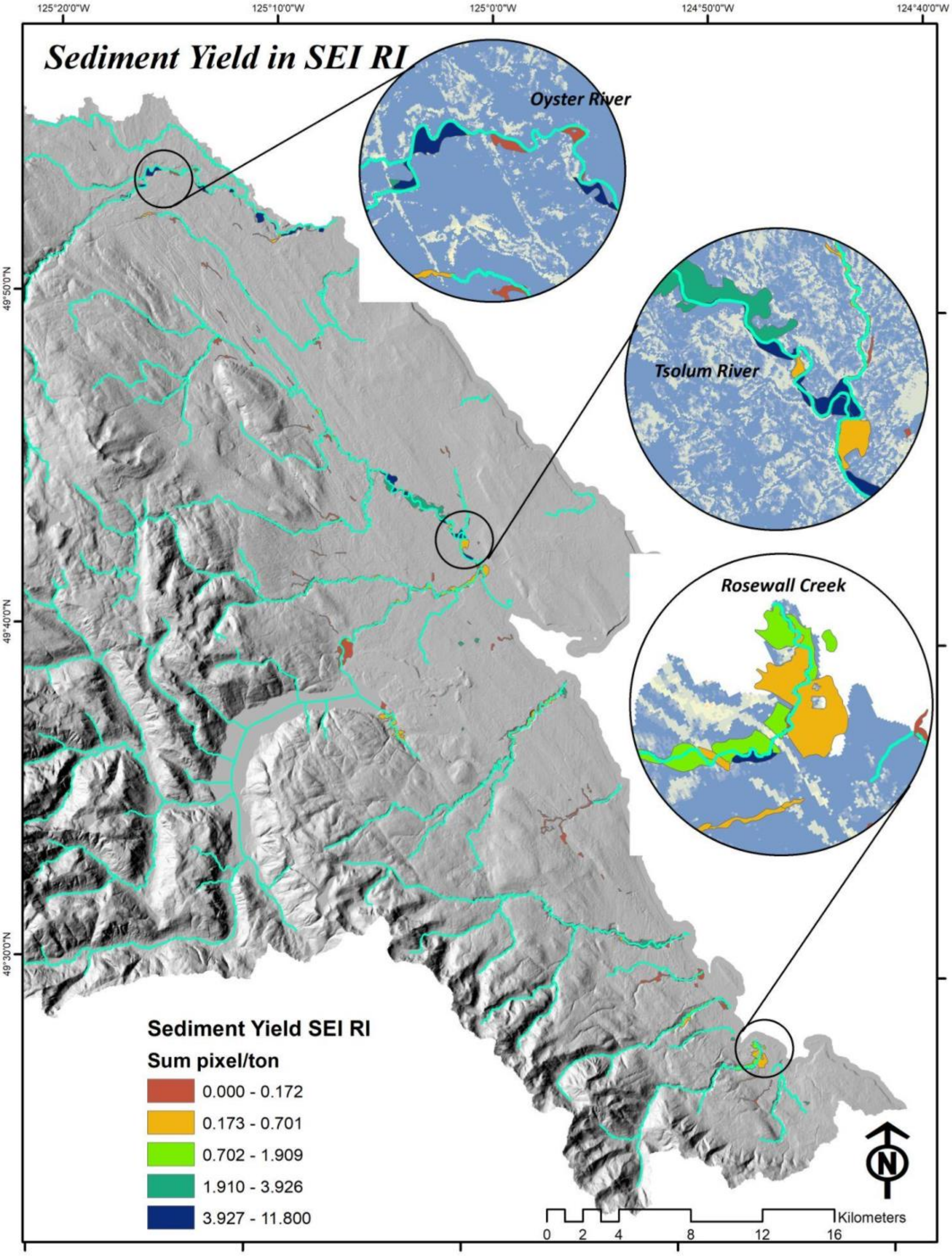


Fig. 28. Sediment yield deposition in riparian areas of SEI polygon

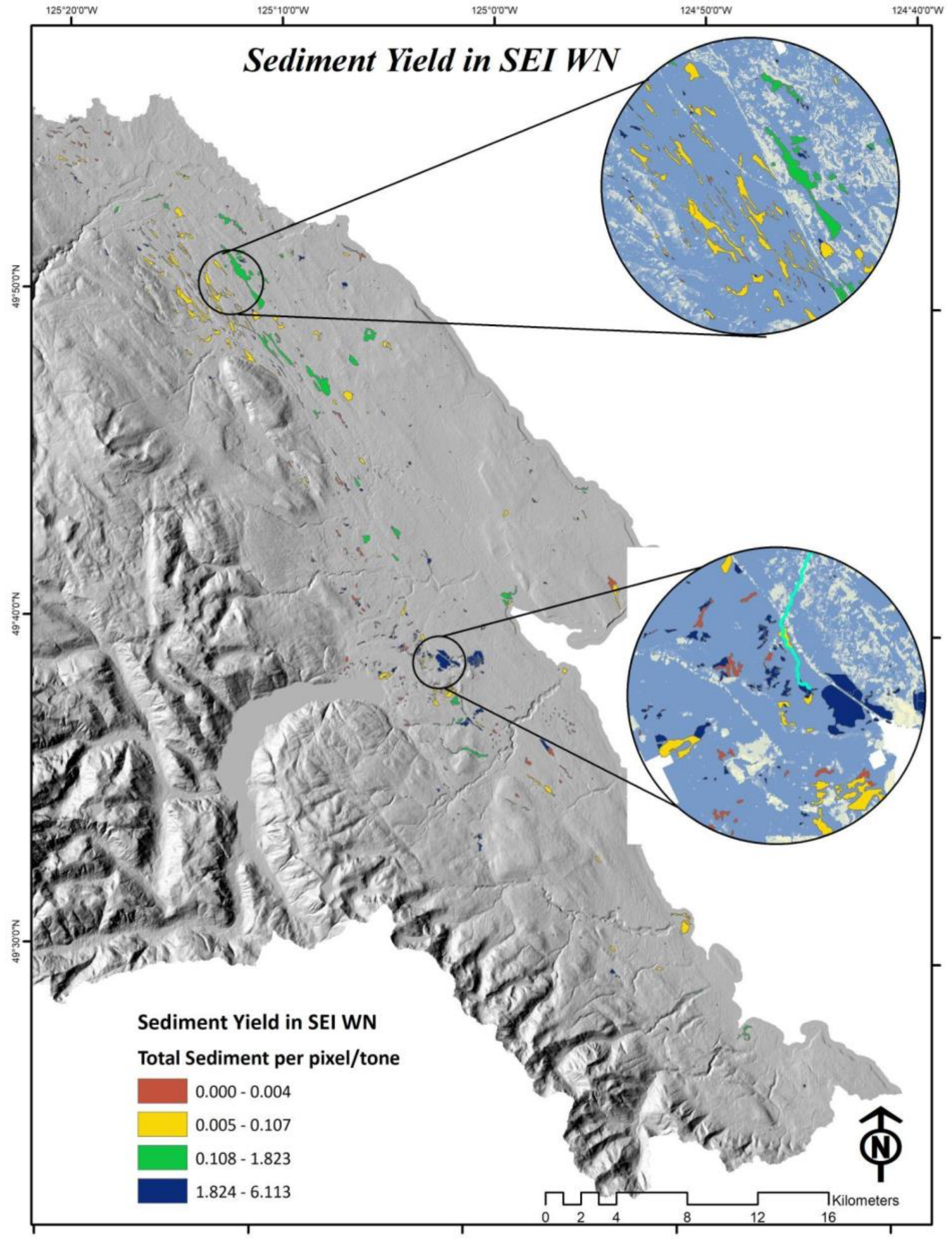


Fig. 29. total sediment Yield in SEI (WN: Wetlands)

The map below represents the sediment load in areas where there is no retention capacity. This means that sediment delivery in these areas is extremely high. The red areas are classified between 0.001 to 4.24 ton/pixel. This is of great importance for conservation goals such habitat banking to spot areas where there is no retention capacity and high sediment yield. The map is a spatial indication of sediment yield capacity in the landscape that can be readily carried into streams.

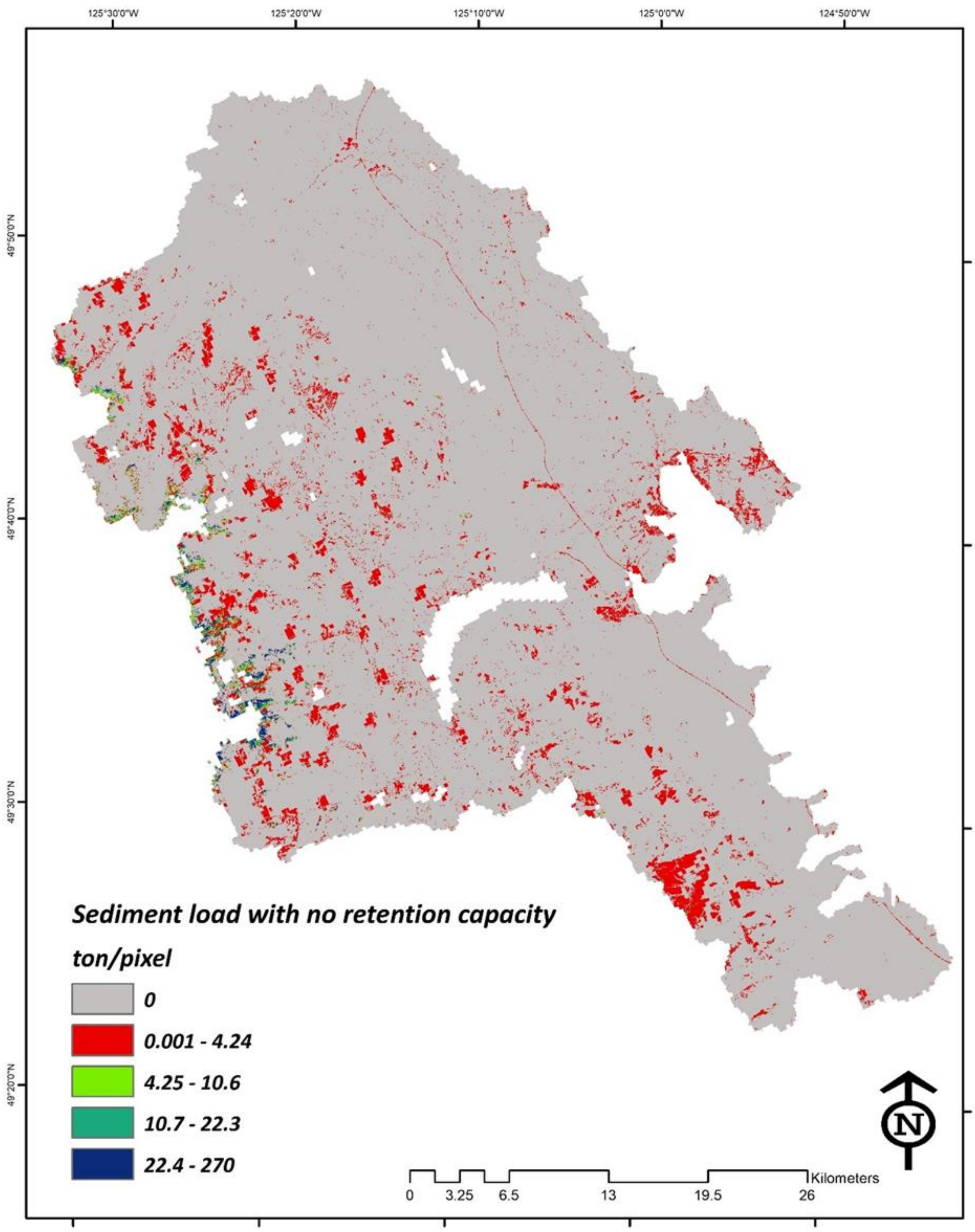


Fig. 30. Sediment yield in areas with no retention capacity

Flow retention in Seasonally flooded Agricultural Fields

In addition to linking the sediment yield with SEI polygons, we also estimated runoff retention capacity in seasonally flooded areas as one of SEI polygons. This finding is not a novel output as previously seasonally flooded agricultural fields are identified, however, our approach spotted areas inside SF areas where there is no retention capacity of quickflow or surface water in the landscape. The findings are linked with SEI polygons and can be useful for agricultural practices.

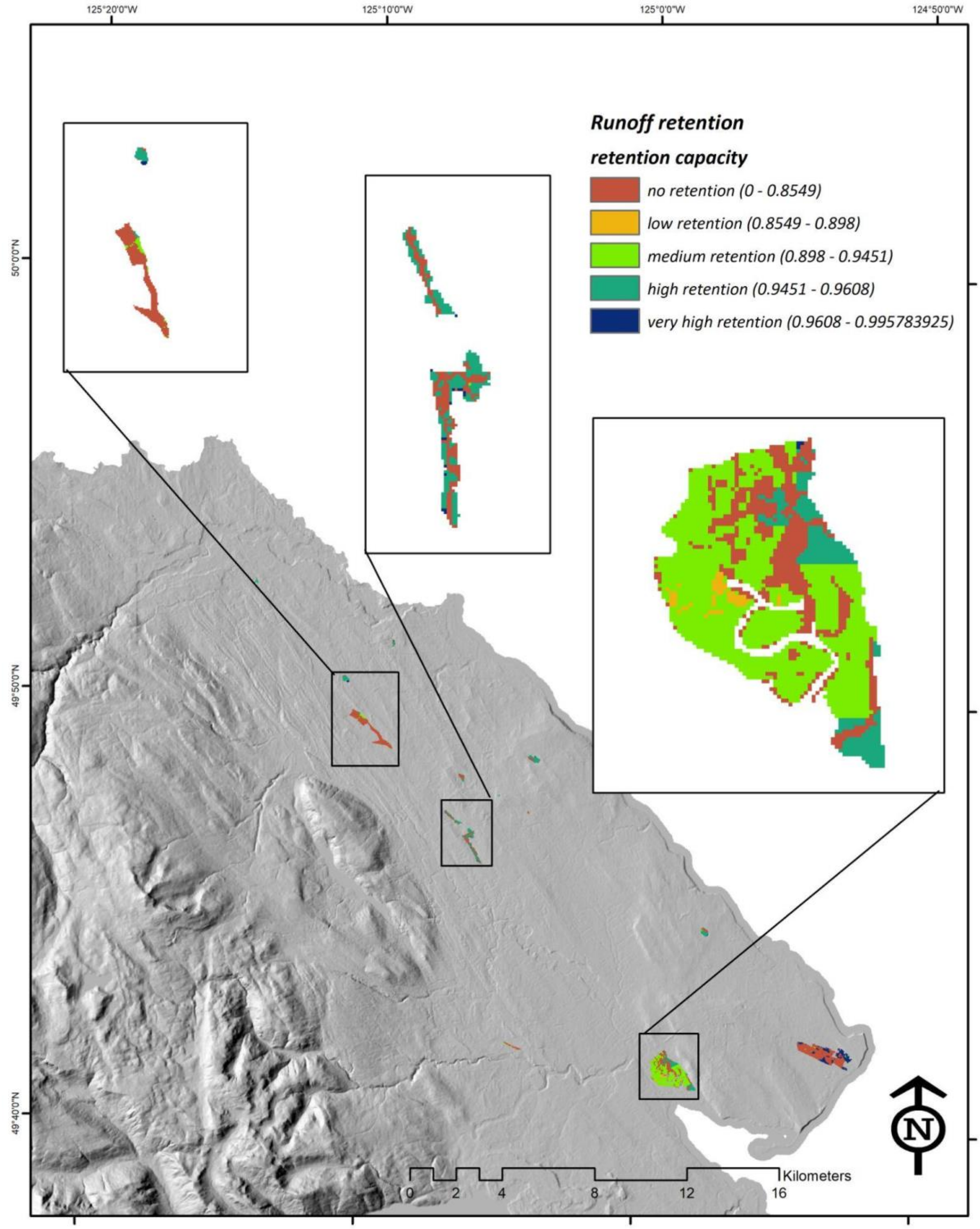


Fig. 31. Runoff retention capacity in seasonally flooded agricultural field of SEI polygon

3.6 Identified new second-growth forest

From the modified age raster (Fig. 9), older second-growth forests (60-100) years were identified that are not included in current SEI polygons (Fig. 32). Some of the forest strands were identified from Google Earth. As the ages of the forests were calibrated from available data, detailed field inspection is required to verify their ages and for deciding whether their inclusion in the SEI layer is required or not.

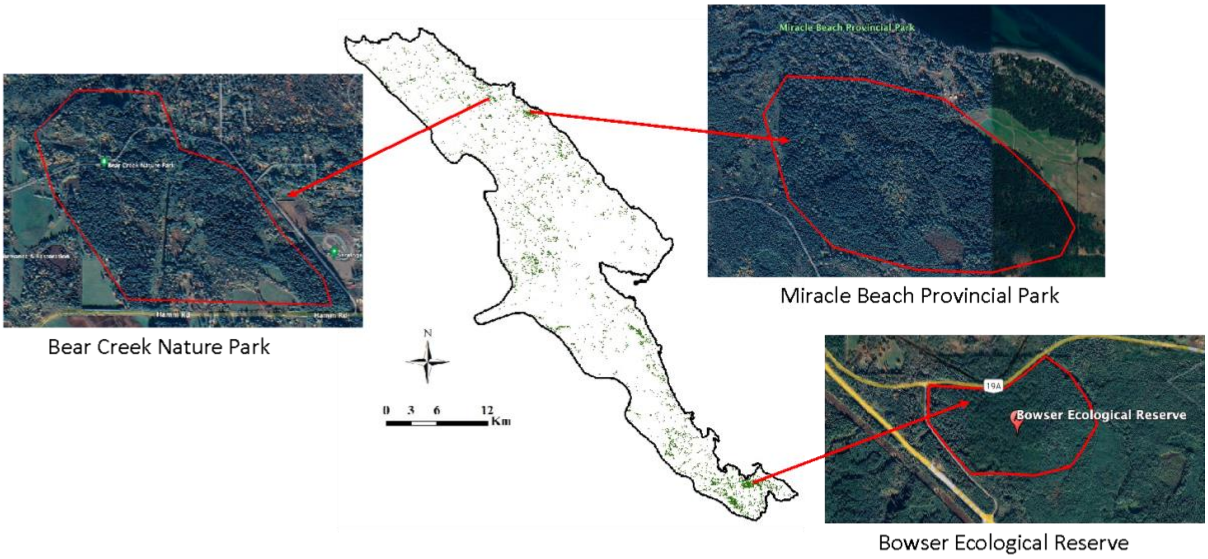


Fig. 32. Older Second Growth Forests (60-100) in Nanaimo Lowland which are not included in the current SEI layer

4. Implications and Recommendations

4.1 Updating Principles, Goals and Objectives

Principles

The updated principles should be easily definable and recognizable to those who do not have a background in conservation.

Connectivity

Connectivity is one of the three principles in the second edition of Nature Without Borders. Connectivity as a conservation strategy is further defined as “a long-term planning approach that involves the protection and rehabilitation of natural connections between important habitats and sensitive ecosystems, allowing for the movement of species and genetic material” (Fyfe, 2013, p. 16). The result of the emphasis on connectivity conservation is that larger areas closer to existing protected areas are prioritized for land acquisition and conservation planning.

This may inadvertently devalue smaller patches of sensitive ecosystems that are not immediately adjacent to an existing protected area. While maintaining that larger, contiguous areas remains a preference for conservation goals, conservation and restoration initiatives worldwide are increasingly recognizing that the quality of the entire matrix (i.e., connectivity across the entire landscape) can improve biodiversity and ecological resilience. In particular, the third principle of connectivity conservation – that "areas with low fragmentation are better than areas with high fragmentation" – is an ongoing debate in conservation science (see Fahrig et al., 2019, Fletcher et al., 2018). Rather, what is not contested is that habitat loss in general and diminishing levels of high-quality habitat led to declining biodiversity and declining ecosystem function.

By expanding the idea of connectivity to consider managing the entire landscape for biodiversity and conservation goals, there is potential to improve the quality of the entire landscape matrix. For example, one could consider a "working lands approach," defined as:

> "Conservation in working landscapes maintains biodiversity, provides goods, and services for humanity and supports the abiotic conditions necessary for sustainability and resilience. These socioecological systems both support biodiversity by providing critical resources and rely on biodiversity (specifically, ecosystem service providers) for sustainable production of food, water, fiber, fuel, and forest products. These landscapes also enhance connectivity to promote the movement of organisms, natural processes, and ecosystem services. Working lands conservation emphasizes the critical role of managing the matrix for species conservation to complement protected areas." (Kremen & Merenlender, 2018, p. 362)

This approach expands connectivity by including nature-friendly land use practices such as agroforestry facilitating connectivity between patches of conserved natural areas. This approach also emphasizes water retention, conserving floodplains and riparian areas.

Restoration

While the first principle should highlight the conservation of remaining ecosystems (including allowing those existing forests to grow and become older forests), there is recognition that many sensitive ecosystems have already declined. In the face of climate change and to allow for ecological resilience, a second principle should focus on restoration – promoting Nature-Based Solutions and improving ecosystem function.

Restoration as a principle recognizes that land use practices have negatively affected natural system processes but have the opportunity and the ability to positively restore some ecosystem functions. Restoration may include a wide range of strategies, including passive restoration (such as conservation and limiting human presence in an area to allow natural regeneration) to active restoration (for example, the Kus-kus-sum project which is actively removing human-built structures. The two would include restoration projects such as K'ómoks Guardians' work in the estuary using traditional fish weirs as protection against geese, which facilitate the natural growth of sedges in the estuary.

Restoration as a guiding principle is timely, as it is currently the UN Decade on Ecosystem Restoration (2021-2030). Restoration is also in line with a landscape approach; it is a major principle behind Forest Landscape Restoration (FLR), which is supported by WWF and the Bonn Challenge (among other global initiatives). FLR is a landscape approach which advocates for multifunctional landscapes and includes all stakeholders in dialogue.

Reconciliation

The CVCP should consider including reconciliation as a driving principle behind an updated Natures Without Borders. Including reconciliation as a principle, rather than as a goal or an objective, emphasizes that reconciliation is an ongoing process. Reconciliation as a principal foreground building an ongoing relationship with KFN, which requires a continual commitment (rather than something that can be completed and achieved). It also foregrounds that any conservation planning tool necessarily involves a recognition that this land is the unceded territory of K'ómoks First Nation, and that there are obligations to both the land and to KFN.

The Truth and Reconciliation Commission calls on governments to adopt the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) and develop specific implementation plans (Call to Action 43 and 44). The BC government passed the Declaration on the Rights of Indigenous Peoples Act in 2019 and in 2022 released an action plan to work towards achieving UNDRIP. Municipalities in the Comox Valley are already starting to work towards creating their own plans and prioritize implementing UNDRIP in municipal activities. Private organizations, including the Comox Valley Conservation Partnership, also play an important role in acknowledging their own role in limiting Indigenous Rights. Conservation initiatives have historically limited Indigenous access to land and resources and facilitated the criminalization of traditional practices. As such, it is particularly important for a conservation strategy to foreground reconciliation as a guiding principle moving forward.

Indigenous Peoples (Coast Salish and later Kwakwaka'wakw) helped shape, create, and maintain the ecosystems (including those captured as SEIs) and landscapes in the area currently known as Comox Valley. The evidence of K'ómoks First Nations ancestors managing the lands and waters can be found in the archaeological record and in oral histories. Oral histories (some of which are documented and published) include lessons of how to co-exist with different species, including behavioural descriptions (see, for example, Boas et al., 2006). Some include stories which show how landscapes were modified by ancestors. Oral histories also document how K'ómoks First Nation members and their ancestors have inhabited the Comox Valley since time immemorial. Existing archaeological evidence also supports long-standing occupation of the area. For example, there is a large fish trap site in the Courtenay estuary, dating between 1,300 and 100 years ago; this shows long-standing maritime management and modification (Greene et al., 2015). In KFN's Cultural Heritage Policy, the mapped areas of "high archaeological potential" often overlap with riparian areas, also considered sensitive ecosystems.

Elsewhere, there is growing evidence that Indigenous Peoples have long modified their landscapes. For example, on the Pacific Northwest Coast, researchers have recently shown that Indigenous land-use legacies in forest gardens close to historical village sites exhibit greater diversity. In this study, researchers found that key species indicated anthropogenic management, and included species (specifically, hazelnut) that fell outside their natural range (Armstrong et al., 2021). Similar studies have not been done for the Comox Valley, and future study is limited by the heavy disturbance regimes and development that have occurred in the area. However, the implication of the study is that Indigenous Peoples across the Pacific Northwest modified landscapes through their land use practices and influenced the ecosystems that remain in the landscape today. Including reconciliation as a guiding principle to an updated Natures Without Borders helps recognize the legacies of Indigenous land use practices and opens space for supporting Indigenous-led initiatives.

Goals and Objectives

Goals and objectives should be re-written to be SMART – Specific, Measurable, Attainable, Relevant and Timely. Prior to updating the objectives, an assessment should be done to measure whether and to what extent the previous objectives and recommendations were adopted and/or achieved. It is clear that CVCP Steering Committee members see the overlap and connections between different priorities and objectives.

Based on the discussions during the input session with the Steering Committee, it is recommended to have a quantifiable goal to conserve existing sensitive ecosystems, another goal to restore ecosystem processes and promote Nature-Based Solutions, and a goal to work toward climate adaptability and resilience.

4.2 Hydrological Services

We identified water quantity and sediment delivery hotspots for ecosystem services supply, but a holistic framework of spatially explicit ecosystem assessment should also consider where they are used, which is necessary for decision-making context. It is recommended to establish further analysis to link ecosystem service provision areas with ecosystem service benefiting areas in the study area to identify ecosystem service flows in the landscape. This is crucial for water consumption by different sections, as well as vulnerability analysis of built capital in the landscape. For example, we identified where there is no quickflow retention which could be interpreted as high flood risk areas; however, we did not identify vulnerability aspects of human dimension, infrastructure and build capital in those areas.

We considered forest age as a proxy for vegetation cover in the landscape to take hydrological responses of different cover types into the modelling process. However, as mentioned in the modelling approach, other important cover types such as cropland, agriculture, and urban areas are mixed in the herb class. This is essential for hydrological modelling to consider different cover types for flood risk reduction.

Our results can support local planners and decision-makers to restore degraded landscapes and protect sensitive ecosystems by identifying key areas of multiple ecosystem services which is a helpful strategy for ecological conservation goals. However, the approach is limited to the current situation (using current normal climate data and land cover), mapping for future conditions under different scenarios is also recommended to cope with climate change impacts and human intervention in the landscape.

4.3 Carbon storage

Carbon storage is high and variable across the Comox Valley, as driven by underlying ecological gradients, forest management history, and development across the landscape. The carbon dataset developed in this report can be used to identify carbon hotspots for conservation as part of a strategy to manage the landscape to mitigate global climate change. The historical carbon storage analysis offers a sense of the potential risks and opportunities for using local land stewardship to contribute to global climate change mitigation. Important limitations are noted and to be improved upon through additional work, including quantifying uncertainty, integrating better data, and mapping hotspots of carbon sequestration.

The large magnitude of carbon storage fluxes from 1984 to 2019 suggests that land management and conservation of carbon can represent an important lever for local efforts to mitigate global climate change. Annual fluxes of carbon from Comox Valley landscapes were observed to range from 5000 to 300,000 Tonnes of CO_2 per year. For comparison, total anthropogenic emissions from the City of Courtenay in 2016 were 92,000 tCO2e (City of Courtenay 2022). Emissions from rural areas of the Comox Valley (not including urban centers) in 2010 were 109,540 tCO2e (CVRD 2015). Thus, it is likely that the way that landscapes are managed has the potential to greatly increase (perhaps double) CO2 emissions from the valley. Meanwhile, the large fluxes suggest that there may also be potential for the landscapes to become a net emitter of CO2, which could be strategized to become a vital part of local government strategies to achieve carbon neutrality.

This carbon storage analysis was made using open-source data and reproducible code so that it can be improved upon in the future. The approach could also be adapted to other landscapes in southwest BC and used to help build a preliminary understanding of carbon storage spatial and temporal dynamics. Our methodology builds off a methodology of the Metro Vancouver carbon storage dataset (Greentree 2019) but relies on coarser datasets (30m land cover mapping instead of 5m land cover; and global forest elevation models rather than local models), which limits some potential uses. For example, it is too coarse to be used for estimating carbon storage within small land parcels but is appropriate for assessing broader patterns and for comparing carbon storage amongst large land parcels. An advantage of the datasets used is that they are free and open source. The code written for this project could be adapted for similar landscape contexts, especially those elsewhere in the Nanaimo Lowlands. Our approach to validate forest ages based on analysis of VRI height-age relationships helps make this workflow extensible to other areas, though, we would recommend that future analysis try to obtain more locally calibrated height-age and age-carbon curves. Making this methodology using open-source tools and data makes it relatively easy to be adapted for other local governments and First Nations to explore the possibility of stewarding their landscapes to mitigate the existential risk of global climate change.

4.4 Limitations

Several important limitations must be noted. In the absence of field data and forest inventory mapping across most of the study sites, this dataset has not been validated. Other analyses such as those done by forestry companies with better data will be more accurate and should be used when and if made available. We recommend that these data be compared with that held by forestry companies to identify opportunities for greater regional collaboration for climate resilience.

The changes in carbon storage depicted by land use must be interpreted cautiously. When tracking changes in a land use category it is important to make sure that the land use category has not changed, to avoid confounding estimates of change and changing areas of that land use. (IPCC 2019). We did not attempt to reconstruct the historical shapefiles of municipal boundaries or parks, but still felt it important to try to depict carbon storage changes within the areas currently under different land uses.

Being able to define the carbon storage values of individual land parcels will require a higher resolution carbon dataset, such as at a 5m or 2m resolution. If a higher resolution landcover and forest elevation dataset was acquired the methods used here could be adapted, but only for the present time. With finer scale, carbon estimates, land parcel data can be overlayed on top of the carbon raster dataset to define the carbon storage of individual parcels. This can be useful for evaluating the climate change mitigation benefits of conservation such as for land acquisitions and for spatial planning of regional park infrastructure. The methods of Greentree 2019 provide one example of how this can be done. We also recommend assessing the carbon sequestration potential of parcels because it is the balance of current carbon storage and future carbon sequestration potential that may best identify climate change mitigation opportunities.

A known bias of this dataset is that we used a single height to forest age curve to estimate forest age based on measured height. The height-to-forest age curve is for a generalized forest condition for Metro Vancouver with a site index of 34. This curve is very well situated for average conditions often Comox Valley within the Nanaimo Lowland portion of the study area, which has a site index of 34. Meanwhile, the higher elevation portions have a lower site index. Although we were able to validate the age estimates against VRI and adjust the ages accordingly, better data would provide a more reliable outcome. In particular, the methodology we used will tend to underestimate the age (and hence carbon storage) of forests growing on unproductive sites where trees may be quite old but still relatively small. The error caused by underestimating the age of forests on unproductive sites may be compounded during backcasting.

We recommend managing carbon storage and sequestration but being careful not to only optimize landscapes for carbon. Plan for resilient carbon storage while co-managing multiple other values. Based on input while presenting this work to municipal staff, we recommend that an important next step in measuring ecosystem services related to climate resiliency is to map the cooling effect of forest canopy and in relation to vulnerable populations. This could help inform urban forestry strategies and the setting of tree bylaws.

4.5 Policy Directions

Jurisdictions in the Comox Valley have taken different approaches to land use planning decisions. There is a variety of different languages used across the jurisdictions, and different definitions of terms. There are also examples of potential best practices and opportunities to learn from neighbouring jurisdictions. The Village of Cumberland offering a financial incentive to use green infrastructure, with a clear definition, holds potential for being a best practice. Its effectiveness should be evaluated to determine its impact.

The City of Courtenay's participation in and support of the Kus-Kus-Sum project is another example of a best practice for promoting ecological restoration and reconciliation. It is still in its early stages but is promising.

The Town of Comox's new bylaws limiting impervious surfaces is also a potential best practice. There should be further evaluated to determine the effectiveness of these two separate bylaws, rather than integrating this regulation into existing building or development bylaws. Regardless, its intention is clear.

There are opportunities for improving citizen engagement and for encouraging green practices. For example, municipal websites can easily add links to existing resources for environmentally friendly practices. The Town of Comox website does not have any "environment" tab.

All jurisdictions acknowledge the importance of consulting KFN, and both City of Courtenay and the Town of Comox list archaeological information as information that may be requested as Development Approval Information. This should be widely adopted and can further be clarified by including the existing mapped areas established in K'ómoks Cultural Heritage Policy. Rather than only requiring archaeological information, it may be requested to include a permit and acknowledgement from K'ómoks.

Several policies in the Comox Valley have the potential to be best practices in environmentally friendly land use planning. It is recommended that municipalities include clear monitoring indicators and set targets according to those indicators to assess policy effectiveness. For example, the Town of Comox sets out clear indicators in their OCP (for example, the number of green-certified buildings). It was outside of the scope of this project to measure policy effectiveness but setting out clear indicators such as these will help municipalities evaluate policy impact on land use and identify target areas for future improvement.

Resources for Future Policy Directions

There is an existing Green Bylaws Toolkit for BC Municipalities. The current edition – Green Bylaws Toolkit for Protecting and Enhancing the Natural Environment and Green Infrastructure – was released in 2021. This document specifically discusses, in detail, the strengths and weaknesses of various policy approach to protect the environment with case studies, including riparian areas, environmental development permit areas, sensitive ecosystems protection, rainwater management, amenity density bonus, tree protection, soil removal, securities and covenants, and others. As such, that work will not be replicated here. Green Bylaws toolkit is available here: www.stewardshipcentrebc.ca/green-bylaws/.

As mentioned above, the CVRD also has a report identifying existing opportunities and practices to facilitate reconciliation. In terms of best practices, one example of a planning collaboration between First Nations and the Canadian government is the North Vancouver Island Marine Plan. KFN, as a member of Nanwakolas Council, was included in the development of a Marine Plan for North Vancouver Island. This plan was developed in collaboration with the provincial government through an initiative called MaPP: Marine Planning Partnership Initiative, based on a marine ecosystem-based management approach.

Through the threats assessment and meetings with municipal planners, priorities for identifying best practices included: community engagement and knowledge-building, incentives for restoration, measurable indicators for natural assets, and opportunities for carbon offsets.

Community Engagement

Saanich has a Naturescape Program which encourages homeowners to “naturescape.” The website includes lists of native species, how to identify native birds, butterflies, etc., includes plans for batboxes; this is part of how Saanich also declared that the UN Decade of Ecological Restoration also applies to Saanich. They also have a map of historical ecosystems in Saanich which could guide restoration projects, raise awareness of how landscapes have changed, and help assist homeowners to identify native species. Making these resources accessible is one part of a community engagement strategy to recognize and value biodiversity.

The City of Delta encourages participation in the City Nature Challenge (https://citynaturechallenge.org/) by promoting it on its website. As part of their participation, they promote guided walks around ecological reserves in their wetlands and estuaries. The City Nature Challenge is an existing, organized event which encourages residents to document the biodiversity in the areas around their homes. This can increase recognition of native species and raise awareness about the importance of maintaining biodiversity.

The City of Kamloops promotes water-conservation landscaping and biodiversity through demonstration gardens in city parks. In MacArthur Park, they have signage identifying their butterfly gardens and xeriscape gardens. By demonstrating this type of landscaping in city parks, the hope is to promote wider adoption in resident properties.

Opportunities for Restoration and Offsets

The carbon storage maps included in this report can be used to help inform decision-making by helping to identify priority areas for parkland acquisition. These areas can then be subsequently measured to confirm the carbon storage estimate and claimed as a recognized carbon offset in the provincial CARIP report as an Option 1 (1E) Avoided Forest Conversion project. To be eligible to be claimed as an avoided forest conversion, “the eligible project lands are owned by the local government and have been reserved or dedicated as a park under section 30 of the Community Charter after the initial signing of the Climate Action Charter in 2007, and that a Forest Management Plan, to be updated every 10 years or more frequently, must be in place within six months of making public the first completed annual Self-Certification Template” – therefore, any parkland acquired after 2007 (or after the signing of the charter, whichever is later), should be eligible to be measured as avoided forest conversion. Metro Vancouver has claimed these credits and the report and measurement are available here: http://www.metrovancouver.org/services/air-quality/AirQualityPublications/LanePropertyAvoidedForestConversionProject.pdf

Kus-kus-sum may be eligible to be registered with the Department of Fisheries as a Habitat Bank. Habitant Banks in Canada are most often created as compensation for development projects which negatively impact fish habitats; these types of projects require a Habitat Alteration, Disruption, or Destruction (HADD) permit and must improve fish habitats elsewhere to offset the disruption. The idea is that there is no net loss of fish habitat. While there are several examples of Habitat Banks in Canada, and the first Canadian Habitat Bank was established in BC in the North Fraser Harbour, there have been numerous problems identified with monitoring and a lack of consistent measurement (Hunt et al., 2011). The City of Edmonton established a Habitat Bank in anticipation of offsetting damage to fish habitats when doing necessary upgrades and repairs to bridges, for example. Creating a Habitat Bank assumed that there will be continued development and alteration of fish habitats.

Local Conservation Funds are often implemented through a parcel tax, and the proceeds are then used for funding conservation and restoration projects. In BC, there is the South Okanagan Conservation Fund and Kootenay Lake Conservation Fund, both of which have successfully funded projects. A guide to implementing conservation funds can be found here: https://soscp.org/wp-content/uploads/2017/12/Conservation-Fund-Guide-2nd-Edition-2017.pdf. In the current context of the Comox Valley, implementing a local conservation fund may not be possible because of the current priority to establish a regional parks service. Since the Regional Parks Service will also be funded through a parcel tax, it may not be feasible at this time to implement this type of fund for restoration work.

The City of Nanaimo has a comprehensive Climate Change Resilience Strategy (2020). Some actions included in the strategy are improving permeable surfaces, restoring riparian areas, reducing emissions, protecting, and replacing trees, and mapping floodplains and shorelines, among others. The actions listed have already been identified and, in some cases, completed by jurisdictions in the Comox Valley. They do not identify funding sources or go into further detail about restoration work. Since jurisdictions in the Comox Valley are doing this work, they could consider consolidating some of these efforts and existing actions into a climate resilience strategy and further identify areas of wildfire risk.

Considering some of the mapped high sediment areas in sources of drinking water in the Comox Valley, jurisdictions may consider researching Water Funds. A toolkit for implementing water funds is available from the US-based Nature Conservancy: https://waterfundstoolbox.org/. There are no current examples of water funds in Canada, although there are successful examples in the US. The concept of a water fund is that downstream users pay an additional fee to upstream landowners as an incentive to maintain riparian areas and ensure water quality. A US example is the Rio Grande Water Fund: a Wildfire and Water Source Protection Project in New Mexico. This fund, targeting primarily ponderosa pine and mixed conifer forests, solicits projects through a Request for Proposals, and funded projects have included forest thinning, stream restoration, education, and monitoring. Another US example includes Brandywine-Christina Healthy Water Fund, which was created in part with municipal funding. Potential challenges to implementing a Water Fund include the low population of the Comox Valley and the high value of timber.

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Appendix A

Table A1. Summary of changes in the number of pixels by land cover class in the study areas. From the 'original' Hermosilla et al. 2019 dataset to the revised dataset, which was used for the carbon analysis. These changes are the result of reclassifying herbs, shrubs, and mixed wood LC pixels within the timber harvesting land base (manually delineated) into coniferous LC.

Landcover type	Original cover of study area (%)	Revised cover of study area (%)	Summary of changes
broadleaf	10.29748	10.29748	No change
coniferous	52.17004	69.06569	Increased: herbs, shrubs, and mixed wood were reclassified as coniferous
exposed_barren_land	3.531763	3.531763	No change
herbs	21.90961	9.469193	Decreased: reclassified as coniferous
mixedwood	0.351917	0.031532	Decreased: reclassified as coniferous
shrubs	7.566313	3.431461	Decreased: reclassified as coniferous
snow_ice	0.475732	0.475732	No change
water	1.882367	1.882367	No change
wetland	0.528023	0.528023	No change
wetland_treed	1.286755	1.286755	No change
total	**100**	**100**	**-**

Appendix B

Calculating soil erodibilty (K factor)

Different soil groups (silt, clay, sand and soil organic carbon) in four standard soil depths 0, 5, 15 and 30 cm and integrated depth for each soil group. We used a prediction algorithm (Hengl et al., 2017) by using global gridded soil information at four above-mentioned standard depths. The algorithm uses the trapezoidal rule for average over depth interval by taking a weighted average of predictions within depth interval using the following equation:

$$\frac{1}{b-a}\int_a^b f(x)dx \approx \frac{1}{(b-a)}\frac{1}{2}\sum_{k=1}^{N-1}(X_{k+1} - X_k)(f(X_k) + f(X_{k+1}))$$

Where N is the number of soil depths, is the k-th depth and F( ) is the value of soil property at depth.

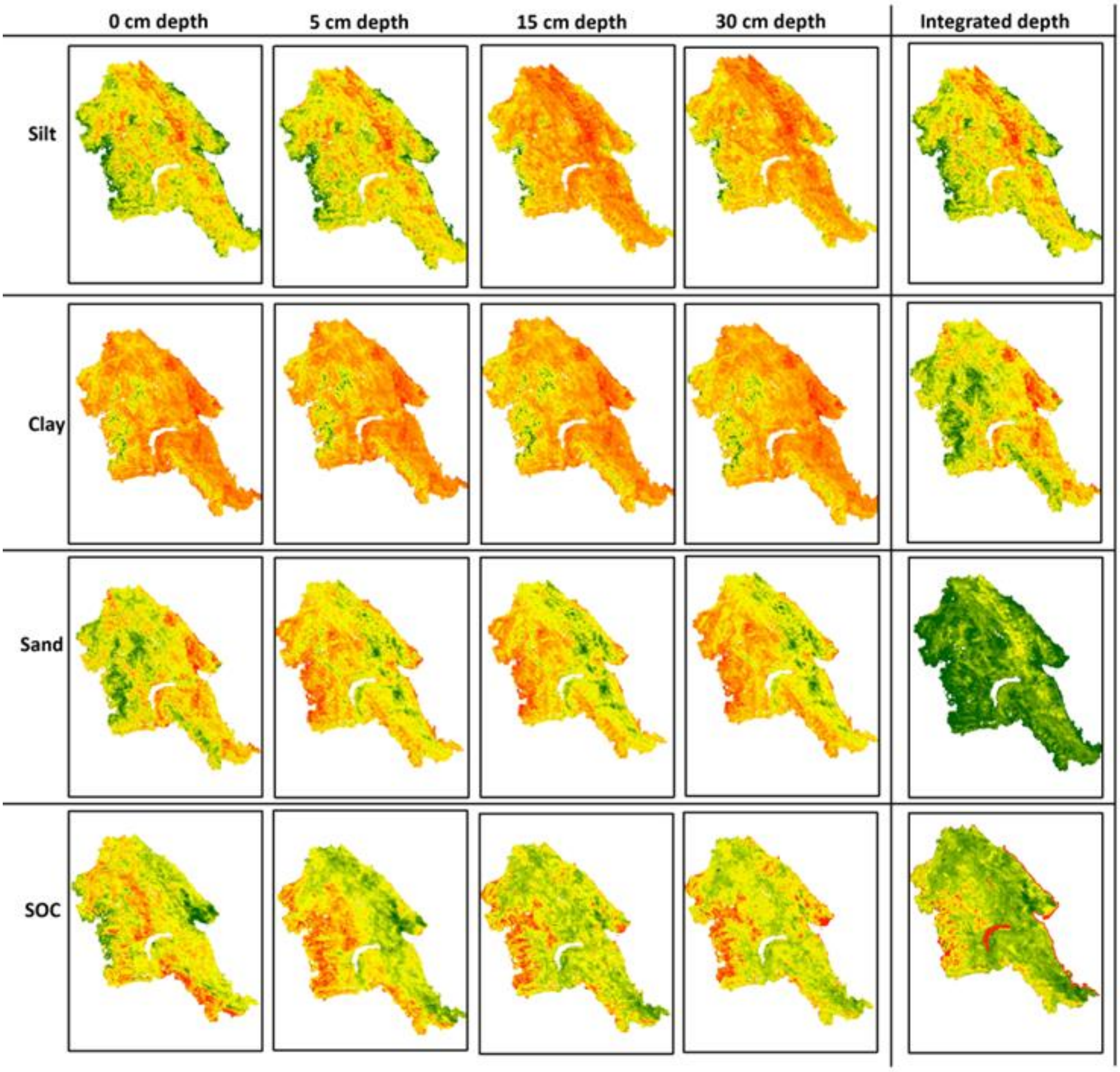

Fig. B1. Four standard soil depths for different soil groups and integrated depth for each group

Appendix C: Input Session Question Guide

Updating Principles, Goals, and Objectives of Nature Without Borders

Background

Four UBC Ph.D. students are working to update Nature Without Borders such that it significantly advances climate mitigation and adaptation, biodiversity conservation, natural asset management and Indigenous rights. Each scholar will contribute to this through their individual thematic objectives and collectively by:

i. Providing recommendations to local governments related to their subject objectives, and
ii. Work in collaboration with the other Scholars in this project to produce the final deliverable
iii. Identify additional important ecosystem services (ES) across the region (broadly or specifically for sensitive ecosystem types) that can potentially be addressed as add-ons to the deliverables (time permitting) or recommended for future research/analysis.

Input Session

Michelle Hak Hepburn, one of the UBC scholars, will lead an interactive session to inform the recommended updates to the principles, goals, and objectives of Nature Without Borders. These questions will also guide research into best practices to include as policy recommendations in the project deliverable. After the session, there is a follow-up online questionnaire to provide additional input.

The 45-minute session will be built around the following questions:

i. What are the guiding principles behind your organization? (one-word answers to create word cloud)

ii. What are the most important principles for an updated Nature Without Borders? (ranking question using Zoom Annotate function)

iii. For each of the previous goals of Nature Without Borders, is this still a goal? Why or why not? (moderated discussion)

Previous goals:

- to stop the loss of sensitive natural areas,
- protect and restore biodiversity and natural system processes,

· preserve healthy water resources

· and preserve access to nature and trails.

iv. What are the threats and obstacles to reaching those goals? (user-generated online sticky notes using Google Jamboard)

Of the threats identified, which are the greatest threats, considering (a) severity and (b) scale? (ranking using Zoom annotate function)

v. Our project explicitly focuses on: climate mitigation and adaptation, biodiversity conservation, natural asset management, Indigenous rights. Specifically, the deliverables focus on carbon sequestration, carbon storage, hydrological ES and flood regulation.

Are these reflected in the NWB goals? (drawing connections using zoom draw function)

vi. In particular, Indigenous rights and climate adaptation and mitigation are not captured by previous NWB objectives and associated recommendations. (moderated discussion)

What does including climate adaptation and mitigation mean to you and your organization?

How can you (and your organization) envision incorporating Indigenous rights?

Definitions

Goal = A formal statement detailing a desired impact of a project such as the desired future status of a target (ideally tied to objectives)

Objective = formal statement detailing a desired outcome of a project (ideally SMART: Specific, Measurable, Achievable, Realistic, and Timely)

Principle = an ideal to guide decision-making processes

Scope = proportion of the target area that is likely to be affected within 10 years

Severity = the level of damage expected within 10 years

(Definitions from the Conservation Measures Partnership and from the WWF Network Standards)

Appendix D: Jurisdictional Scan

Provided as supplementary excel file)