https://doi.org/10.1038/s44183-025-00125-6

A blueprint for national assessments of the blue carbon capacity of kelp forests applied to Canada's coastline

Check for updates

Jennifer McHenry[1] ✉, Daniel K. Okamoto[2], Karen Filbee-Dexter[3], Kira A. Krumhansl[4], Kathleen A. MacGregor[5], Margot Hessing-Lewis[6,7], Brian Timmer[1], Philippe Archambault[8,9], Claire M. Attridge[10], Delphine Cottier[9], Maycira Costa[11], Matthew Csordas[1], Ladd E. Johnson[9], Joanne Lessard[12], Alejandra Mora-Soto[11], Anna Metaxas[13], Christopher K. Neufeld[7,14,15], Ondine Pontier[6], Luba Reshitnyk[6], Samuel Starko[3], Jennifer Yakimishyn[16] & Julia K. Baum[1]

Kelp forests offer substantial carbon fixation, with the potential to contribute to natural climate solutions (NCS). However, to be included in national NCS inventories, governments must first quantify the kelp-derived carbon stocks and fluxes leading to carbon sequestration. Here, we present a blueprint for assessing the national blue carbon capacity of kelp forests in which data synthesis and Bayesian hierarchical modeling enable estimates of kelp carbon production, storage, and export capacity from limited data. Applying this blueprint to Canada's extensive coastline, we estimate kelps hold 0.6 to 2.8 Tg C in short-term biomass, producing 1.1 to 6.2 Tg C yr^{-1}, of which 0.04 to 0.4 Tg C yr^{-1} could be exported to the deep ocean. While modest compared to terrestrial sinks, our findings suggest kelps have comparable carbon sequestration to marine and freshwater wetlands, warranting further consideration in Canada's NCS inventories. Our transparent, reproducible blueprint represents an important step towards accurate carbon accounting for kelp forests.

As the urgency of addressing climate change intensifies, natural climate solutions (NCS) involving habitat interventions to enhance natural carbon sinks have emerged as distinct components of countries' mitigation strategies[1,2]. However, most NCS assessments focus on forests, grasslands, and freshwater wetlands, with less attention on the vast carbon reservoirs found in the ocean[1,3,4]. In the coastal zone, blue carbon ecosystems (BCEs)–seagrass meadows, salt marshes, and mangrove forests–contribute to carbon sequestration in the ocean by converting carbon dioxide (CO_2) removed from the atmosphere and/or water-column into biomass, and by promoting the burial of organic material in benthic sediments[2,5–8]. BCE standing biomass can persist for decades, and sedimentary carbon stocks can be preserved for centuries to millennia when undisturbed[9–11]. As a result, these systems remove carbon from the atmosphere and water-column where it would otherwise exchange as atmospheric CO_2 and exacerbated climate change[8]. Since many BCEs have declined significantly over the past century[12], conservation and improved management of these ecosystems are increasingly seen as low regret strategies for avoiding further CO_2 emissions. Similarly, restoration has been proposed as a strategy to enhance natural carbon sequestration in the ocean[1,2,13].

Kelp forests, composed of large brown seaweeds from the order Laminariales, have traditionally not been considered BCEs, due to their lack of roots and local carbon burial in sediments[14,15]. However, recent work identifies kelp forests as emerging BCEs[16] because of their ability to efficiently assimilate CO_2[17], near global distributions[18,19], role as producers of carbon-rich material, and potential to facilitate carbon export to depositional environments where sequestration occurs[20–24]. Much like terrestrial forests, kelps form expansive and highly productive vegetated canopies, with some species extending from the benthos to the surface (i.e., surface kelps)

[1]University of Victoria, Department of Biology, Victoria, BC, Canada. [2]University of California Berkeley, Department of Integrative Biology, Berkely, CA, USA. [3]University of Western Australia, Perth, WA, Australia. [4]Fisheries and Oceans Canada, Bedford Institute of Oceanography, Dartmouth, NS, Canada. [5]Fisheries and Oceans Canada, Maurice Lamontagne Institute, Mont-Joli, QC, Canada. [6]Hakai Institute, Campbell River, BC, Canada. [7]University of British Columbia, Institute for the Oceans and Fisheries, Vancouver, BC, Canada. [8]ArcticNet, Takuvik International Research Laboratory, 11 CNRS Québec City, QC, Canada. [9]Université Laval, Department of Biology, Québec City, QC, Canada. [10]Simon Fraser University, Department of Biological Sciences, Burnaby, BC, Canada. [11]University of Victoria, Department of Geography, Victoria, BC, Canada. [12]Fisheries and Oceans Canada, Pacific Biological Station, Nanaimo, BC, Canada. [13]Dalhousie University, Department of Oceanography, Halifax, NS, Canada. [14]LGL Limited, Sidney, Canada. [15]University of British Columbia, Okanagan, Canada. [16]Pacific Rim National Park Reserve, Parks Canada, BC, Canada. ✉e-mail: jennmchenry@uvic.ca

and others forming dense submerged beds on the seafloor (i.e., subsurface kelps). While most kelp production enters marine food webs as particulate and dissolved organic carbon (POC and DOC, respectively) and is remineralised in the short-term[25], a portion has the potential to become sequestered and stored for geological timescales (i.e., 100 s to 1000 s of years) in various natural ocean carbon sinks[14,17,26]. There are three main pathways for kelp carbon sequestration: (1) some portion of kelp DOC is or becomes refractory DOC (i.e., inaccessible to microbial communities) with residence times ranging from decades to centuries when exported below the photic zone[20,27]; (2) kelp POC in the form of dislodged or fragmented biomass is transported and buried on the continental shelf (depths <200 m) in seabed sediments and/or the sediments of other BCEs (e.g., seagrass meadows) for similar timescales[28,29]; and (3) kelp POC reaches the deep ocean (depths >200 m), where it can be preserved for centuries to millennia because of the limited potential for exchange with the surface ocean[20,30].

Global assessments show considerable potential for carbon assimilation through kelp productivity[17,18]. Yet whether kelp forests can provide viable NCS remains unclear because of the data gaps, process uncertainties, and challenges associated with estimating the relative magnitude of kelp carbon entering the three main carbon sequestration pathways[31]. Substantial stretches of temperate and sub-arctic coastlines are suitable habitats for kelps, but the actual extent of kelp forests is not fully mapped in most countries[32], has undergone significant changes over the last century[33], and is likely to exhibit seasonal and interannual variability in both extent and productivity[34]. Kelp-derived carbon stocks and fluxes (i.e., biomass, productivity, export, and sedimentary accumulation rates) leading to carbon sequestration are also uncertain because of natural variation and incomplete knowledge of their distribution, production, and POC and DOC fates. Moreover, not all exported kelp carbon will be stored for long enough to be considered relevant for climate change mitigation (i.e., >100 years) and not all kelp carbon that is stored will fall into existing carbon accounting and verification standards (i.e., within verifiable and governable reservoirs inside a country's exclusive economic zone; EEZ)[14,15]. Together, these factors complicate efforts to assess the potential contributions of kelp forests to national NCS inventories.

To facilitate accurate carbon accounting, we present a blueprint for producing national assessments for kelp forests (Fig. 1). Combining kelp data collation with Bayesian hierarchical modeling, this transparent and

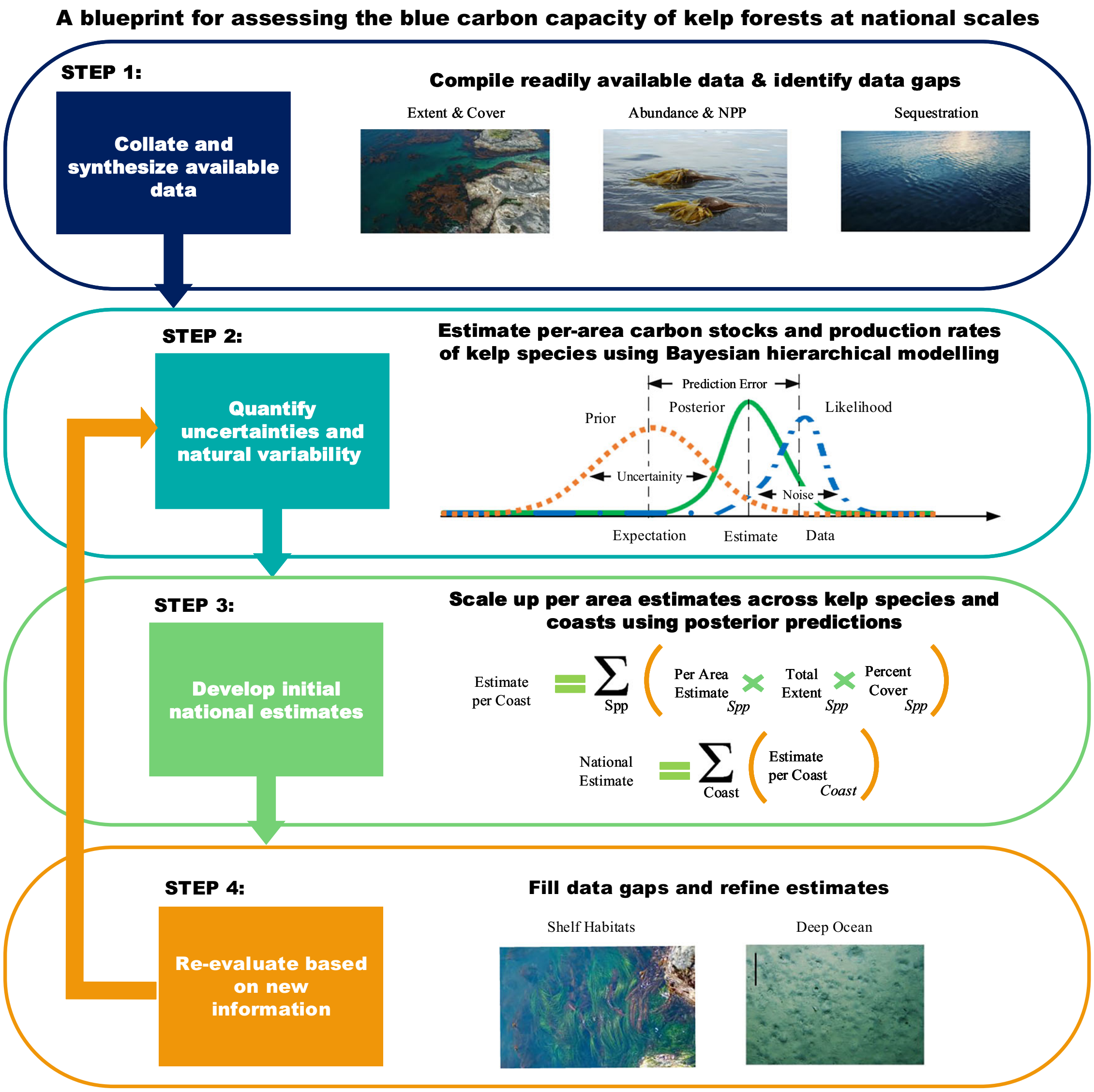

Fig. 1 | A proposed blueprint for national assessments of the blue carbon capacity of kelp forests. Our proposed blueprint involves steps to compile and synthesize available kelp data (Step 1), quantify uncertainties and natural variability in potential rates of carbon production and storage by kelp species (Step 2), develop initial estimates of the carbon production, storage, and export capacity of kelp forests at national scales (Step 3), and refine assessments based on new information and data (Step 4).

Table 1 | Comparison of the estimated extents, carbon stocks, carbon production rates, and carbon sequestration capacity of kelp forests, seagrass beds and salt marshes in Canada

Ecosystem	Areal extent (Mha)	C stock per-area (Mg C ha^{-1})	C production per-area (Mg C ha^{-1} yr^{-1})	C sequestration per-area * (Mg C ha^{-1} yr^{-1})	Total C stock capacity (Tg C)	Total C production capacity (Tg C yr^{-1})	Total C sequestration capacity* (Tg C yr^{-1})
Kelp forests							
Biomass:	1.8[+] (0.8–6.3)	0.8[+] (0.4–1.2)	3.5[+] (1.3–6.7)	0.6[+] (0.3–1.5)	2.8[+] (0.6–4.4)	6.4[+] (1.1–11.6)	0.4[+] (0.04–1.0)
Seagrass meadows							
Biomass:	0.8 (0.2–1.4)[a]	0.1 (0.06–0.2)[b]	ND	NA	0.08 (0.01–0.3)	ND	NA
Soils:	0.8 (0.2–1.4)[a]	88.2 (50.2–380.1)[c]	NA	0.2 (0.04–0.9)[a,c]	70.6 (10.0–532.1)	NA	0.2 (0.01–1.3)
Salt marshes							
Biomass:	0.4[d]	ND	ND	NA	ND	ND	NA
Soils:	0.4[d]	80.4 (35.0–173)[e]	NA	2.0 (0.6–9.3)[e]	32.2	NA	0.8

Parenthetical values represent the high (low – maximum) estimate values reported by this study and in the literature. *Carbon sequestration for kelp forests is calculated in terms of the estimated export of kelp detrital carbon to deep ocean sinks; carbon sequestration for seagrasses and salt marshes is calculated in terms of the amount of carbon accumulation in sediments. ND signifies no data for a particular field; NA signifies there the field is not applicable for a given ecosystem.

Data sources: [+]This study; [a]Drever et al. 2021, [b]Prentice et al. 2018, [c]Prentice et al. 2020, [d]Rabinowitz & Andrews, [e]Kelly et al. 2023.

reproducible analytical framework estimates the carbon stock, production, and export capacity of kelp forests—as important precursors to carbon sequestration—while explicitly acknowledging the inherent data limitations and uncertainties that most countries face in this regard. We apply this blueprint to Canada, a country accounting for 16.2% of the world's coastline[35], with expansive kelp forests in the Atlantic, Pacific, and Arctic oceans. Two major surface canopy species, giant kelp (*Macrocystis pyrifera*) and bull kelp (*Nereocystis luetkeana*), form extensive floating forests along the Canadian Pacific, while subsurface species from the genera *Laminaria, Saccharina, Alaria, Agarum*, and others form dense submerged beds on their own, or as an understory below surface kelps, along substantial stretches of the Canadian coastline[36]. By piloting our blueprint in Canada, with its diverse kelp ecosystems and heterogenous coastal conditions, we demonstrate its broader utility for integrating kelp forests into national NCS inventories.

Results

Kelp forest blue carbon blueprint

Our blueprint for national assessments of the blue carbon capacity of kelp forests involves: (1) compiling and synthesizing available data on the areal extent, cover, abundance, net primary productivity (NPP) and relative export rates of kelp-derived carbon via three main carbon sequestration pathways, (2) evaluating the potential natural variation in the carbon stocks and carbon production rates for kelp species, (3) developing initial estimates of the standing carbon stock, production, and export capacity of kelp forests, and 4) refining assessments based on new information and data (Fig. 1). For reproducibility, we provide a blueprint workflow and methodology for conducting an extensive collation of available kelp datasets (Supplementary Note). We also provide R scripts enabling users to develop Bayesian hierarchical models ('Brms' package) to estimate the posterior mean carbon stocks and production rates of different kelp species based on limited available data and prior information, as well as templates for scaling up per-area estimates to a national scale (Supplementary Data). Below we illustrate the blueprint's utility through an application to Canada.

First blueprint application: Canadian kelp forests

We first compiled a database of kelp records from 36 published studies and monitoring programs (Supplementary Table 1; Supplementary Fig. 2) describing the areal extent, cover, abundance (i.e., biomass and density), and NPP of subtidal kelp species across Canada's Pacific, Atlantic and Arctic coasts (Fig. 1, Step 1). Our search targeted available data for surface kelps found on the Pacific coast and subsurface kelps found across Canada's three coasts, revealing that eleven of the 18 subtidal kelp species in Canada had sufficient data records to be included in further analyses. These include both surface kelp species and seven of the 15 subsurface kelps on the Pacific coast, five of the seven subsurface species on the Arctic coast, and three of the five species on the Atlantic coast (Supplementary Table 2). Lastly, we collated available information on the fraction of kelp-derived carbon entering the three main pathways for carbon sequestration in Canada. We acquired estimates of the rate of kelp carbon export (i.e., the fraction of kelp POC transported) to the deep ocean from one published study[24] (Supplementary Table 3) but found there is currently insufficient information to evaluate the amount of kelp carbon entering the other two pathways (i.e., refractory DOC and shelf burial) in Canada.

Kelp forest extents

Subsurface kelps. Next, since synoptic maps were unavailable, we produced a range of extent estimates for subsurface kelp forests in Canada (i.e., a maximum, high and low) using available depth, substrate, and kelp percent cover data (Supplementary Table 4). To represent the hypothetical maximum limit for where subsurface kelps could occur, we calculated the area of rocky reefs (i.e., bedrock and boulders habitats) from mean-low water out to 20 m water depth. Using these depth and substrate constraints, we estimated that subsurface kelp forests cover up to 6.3 million hectares (Mha) (Table 1). Most of the total extent (approximately 71%) was estimated to occur in the Arctic (5.5 Mha) with Atlantic and Pacific kelp forests covering 1.3 and 0.5 Mha, respectively (Supplementary Table 4). Given that kelp does not always completely cover benthos, we then produced more constrained high and low estimates, using the upper and lower quantiles of observed of subsurface kelp percent cover (Supplementary Table 1), acknowledging the potential for variation across coasts, seasonally, and interannually. While the exact extent of subsurface kelps is still unknown, we estimated from these high and low criteria that extent falls between 0.8 and 3.9 Mha (Supplementary Table 4).

Surface kelps. As a special case found on the Pacific coast, we also produced a range of extent estimates for surface kelps using available depth and substrate data, aerial surveys, and remote sensing products (Supplementary Fig. 3). First, as the hypothetical maximum limit, we calculated the area of rocky reefs from mean-low-water out to 10 m water depth (Supplementary Fig. 4). Then, as a high estimate, we used historical shoreline maps derived from oblique aerial survey imagery collected by the British Columbia Shore Zone Survey between 2004 and 2007 identifying shallow rocky reefs that were previously covered by surface kelps. Finally, we used recent global maps derived from Sentinel-2 satellite imagery which show the average detection of surface kelps between 2015 and 2019. Due to its smaller area, more precise methodology,

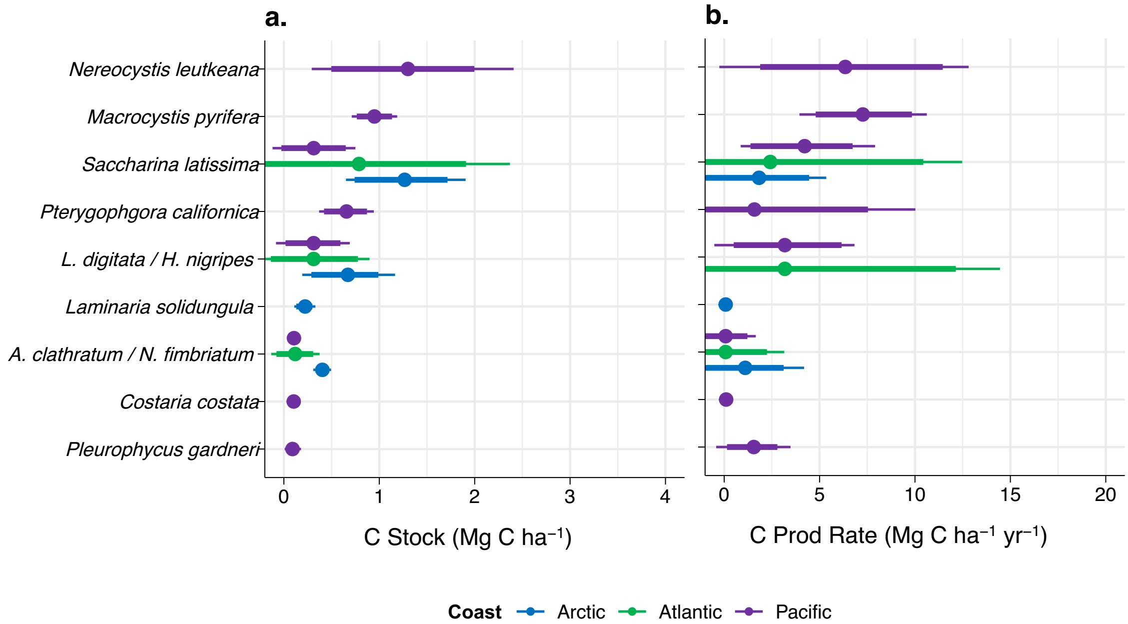

Fig. 2 | Per-area estimates of blue carbon associated with subtidal kelp species in Canada. Panels depict the posterior mean estiamtes of the (**a**) carbon stock (Mg C ha^{-1}) and (**b**) carbon production (Mg C Ha^{-1} yr^{-1}) capacity of kelp species across Canada's three coastlines (Pacific = purple; Atlantic = green; Arctic = blue) according to Bayesian hierarchical models. Posterior mean estimates (and 90% credible intervals) are shown for each species, representing the average posterior predictive distribution conditional on the observed data and prior information. The inner and outer bars show the credible intervals representing the range of values within which the true mean estimates are likely to occur with 80% and 90% probability based on the final models. Kelp species include: *Macrocystis pyrifera*, *Nereocystis leutkeana*, *Costaria costata, Agarum clathratum / Neoagarum fimbriatum*, *Laminaria digitata / Hedophyllum nigripes, Laminaria solidungula*, *Pterygophera californica*, *Pleurophycus gardneri*, and *Saccharina latissima*.

conservative assumptions, and later collection period, we considered this the low estimate for surface kelps. According to this analysis, surface kelps cover up to 0.3 Mha with a more constrained range between 0.005 and 0.11 Mha (Supplementary Table 4).

Per-area carbon stocks and production rates of kelp species

Bayesian hierarchical models revealed significant differences in per-area carbon stocks and productivity within and among kelp species in Canada (Fig. 1, Step 2), with surface kelps being higher on average than subsurface species (Fig. 2). Giant and bull kelp stored more carbon per-area in their canopy biomass than six of the seven subsurface species (1.30 Mg C ha^{-1} and 0.95 Mg C ha^{-1}, respectively), with over 80% conditional support for differences amongst the posterior mean predictions (Fig. 2a, Supplementary Table 5). Giant and bull kelp also had the highest annual carbon production rates per-area (7.26 Mg C ha^{-1} yr^{-1} and 6.35 Mg C ha^{-1} yr^{-1}, respectively), producing more than twice the amount of carbon annually of other kelp species (Fig. 2b; Supplementary Table 5). While certain subsurface kelps (e.g., *Saccharina latissima*) had comparable estimated carbon stocks and production rates to surface kelps, most had much lower estimated carbon stocks per-area—ranging from 0.01 Mg C ha^{-1} (*Pleurophycus gardneri*) to 0.66 Mg C ha^{-1} (*Pterygophora californica)*—and carbon production rates per-area —ranging from 0.08 Mg C ha^{-1} yr^{-1} (*Agarum clathratum / Neoagarum fimbriatum*) to 3.18 Mg C ha^{-1} yr^{-1} (*Laminaria digitata / Hedophyllum nigripes*) (Fig. 2).

Per-area carbon stocks, production, and export rates of kelp forests by coast

Across Canada's three coasts, we found considerable variation in the estimated per-area carbon stock and production rates of kelp forests due to differences in species composition and peak standing biomass (Fig. 3). Overall, Pacific kelp forests had the largest estimated carbon stocks per-area (1.2 Mg C ha^{-1}), along with the largest number of kelp species ($N = 17$), and the highest estimated annual carbon production rates (6.7 Mg C ha^{-1} yr^{-1}) (Fig. 3a). By comparison, Atlantic and Arctic kelp forests had lower species richness ($N = 7$ and 5, respectively) and lower estimated carbon stocks held in biomass (0.4 and 0.8 Mg C ha^{-1}, respectively), as well as much lower annual carbon production rates (2.7 Mg C ha^{-1} yr^{-1} and 1.3 Mg C ha^{-1} yr^{-1}, respectively) (Fig. 3b).

As an important precursor to carbon sequestration in the deep ocean, we estimated carbon export fluxes from kelp forests to the deep ocean, which we define as the magnitude of kelp-derived carbon exported from the coastal domain to deep waters (i.e., the 200 m isobath) beyond the continental shelf break. Based on a recent published global model of coastal residence times, approximately 22.0% (SD = 12.0%) of kelp detritus is likely to reach the shelf break before decomposing on the Pacific coast compared to 10.8% (SD = 6.7%) in the Atlantic and 8.8% (SD = 2.8%) in the Arctic (Supplementary Table 3). This suggests that 1.5 Mg C ha^{-1} yr^{-1} (0.7–2.3 Mg C ha^{-1} Yr^{-1}) could be exported to deep waters from Pacific kelp forests compared to 0.3 Mg C ha^{-1} yr^{-1} (0.2–0.4 Mg C ha^{-1} yr^{-1}) from Atlantic kelp forests and 0.1 Mg C ha^{-1} yr^{-1} (0.01 – 0.2 Mg C ha^{-1} yr^{-1}) from Arctic kelp forests (Fig. 3c). Since there was no data available on the fraction of kelp-derived carbon being exported to shelf sediments and refractory DOC pools, we were unable to evaluate these other carbon sequestration pathways.

First national estimates for Canadian kelp forests

To produce national estimates for Canadian kelp forests, we combined each of the kelp extent estimates (i.e., maximum; high, and low range) with the per-area carbon stock, carbon production, and carbon export estimates (Fig. 1, Step 3). Comparing first by region, we found contrasting patterns across Canada's three coasts. Arctic kelps had the highest total carbon stock (3.5 Tg; 0.6–2.5 Tg C) and production capacity (5.8 Tg C yr^{-1}; 1.0 – 4.1 Tg C yr^{-1}) due to their disproportionately large extents (Fig. 4a, b). Pacific kelps had the highest estimated carbon fluxes to the deep ocean (0.5 Tg C yr^{-1}; 0.01–0.2 Tg C yr^{-1}), reflecting their higher per-area carbon production rates and greater potential for detrital export beyond the shelf break (Fig. 4c).

Nationally, assuming kelps are at their maximum extents, we estimate that Canadian kelp forests contain up to 4.4 Tg C in standing biomass and

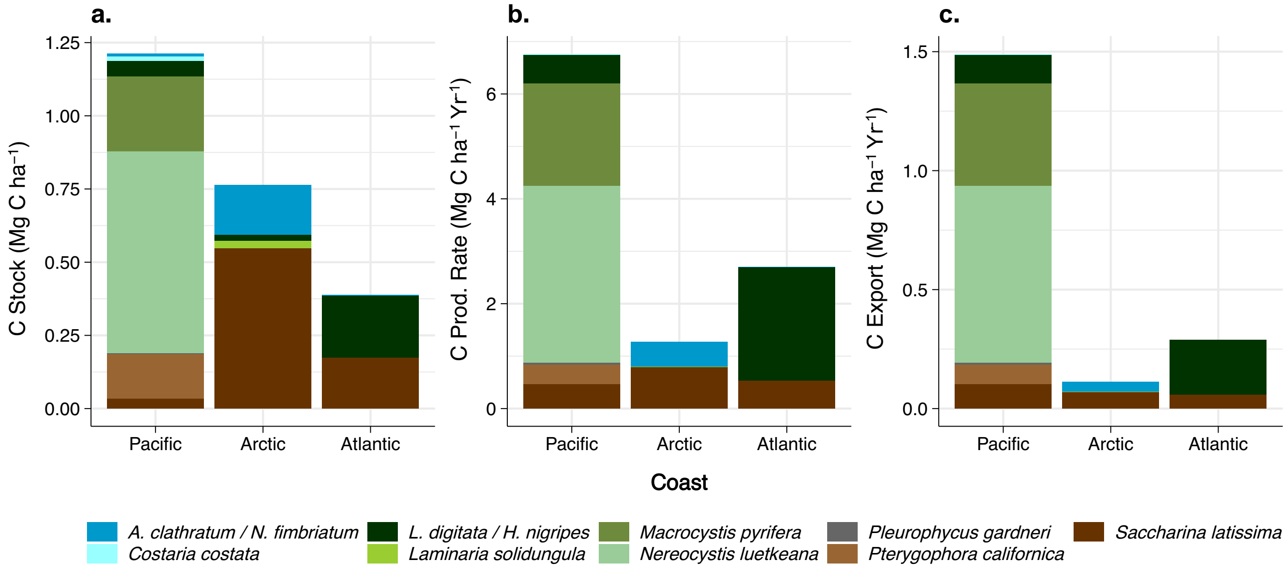

Fig. 3 | Per-area posterior mean estimates of blue carbon associated with subtidal kelp communities across Canada's coastline. Panels depict the posterior mean estimates of the (**a**) carbon stocks (Mg C ha^{-1}), **b** carbon production (Mg C ha^{-1} yr^{-1}), and (**c**) carbon export (Mg C ha^{-1} yr^{-1}) capacity of subtidal kelp communities on Canada's three coasts. Stacked bar plots show the summed posterior means across kelp species and coasts according to Bayesian hierarchical models, weighted by the relative abundance of kelp species on each coast.

produce up to 11.6 Tg C Yr^{-1} through annual primary production. Of this, an estimated 1.0 Tg C yr^{-1} may be exported to the deep ocean (Table 1). However, under more constrained and realistic kelp extent scenarios, we estimate that the total carbon stock capacity ranges between 0.6 and 2.8 Tg C, the annual carbon production capacity ranges between 1.1 and 6.2 Tg C yr^{-1}, and the annual deep ocean export capacity ranges between 0.04 and 0.4 Tg C yr^{-1}.

Discussion

National assessments of BCEs such as seagrasses, salt marshes, and mangroves are becoming more prevalent[2,37], paving the way for their incorporation into NCS inventories. However, comparable evaluations for kelp forests are currently unavailable for nearly 90% of the 150 countries with kelp forests[14], due to existing data gaps and the difficulty of accurately estimating the kelp-derived carbon stocks and fluxes leading to sequestration in various ocean sinks (i.e., DOC pools, shelf sediments, and the deep ocean). While kelp forests cannot currently be fully accounted for in NCS inventories in most countries, our findings indicate that they merit further research and could be worth accounting for in the future once the critical data needs and research gaps we identify have been addressed. Our reproducible blueprint, applied to Canadian kelp forests, provides a framework for other nations seeking to integrate kelp forests into their NCS inventories.

Our assessment found the carbon production capacity of Canadian kelp forests to be substantial (maximum: 11.5 Tg C yr^{-1}; constrained range: 1.1–6.3 Tg C yr^{-1}). Although this value is low compared to recent global estimates of kelp carbon production (~1.5% of global estimated NPP), these analyses are not directly comparable as we used a more conservative depth cut-off to calculate kelp forest extents (20 m compared to 30 m)[18]. Additionally, we found that Canadian kelp forests may contribute up to 1.0 Tg C yr^{-1} (more realistically between 0.04–0.4 Tg C yr^{-1}) of export of carbon-rich material to the deep ocean, where it may be sequestered and stored for time-scales relevant to climate mitigation efforts (<100 years). While our assessment most likely represents an upper bound for deep ocean export and potential sequestration, it could in theory still be an underestimate overall considering that a fraction of kelp-derived carbon becomes buried in shelf sediments and enters refractory DOC pools[14,17]. Compared to terrestrial ecosystems, kelp forests are likely to play a more modest role in the NCS components of Canada's climate change mitigation strategy[3]. As examples, conservation pathways for grasslands, peatlands, and forests have been estimated to sequester 3.5 Tg C Yr^{-1}, 2.8 Tg C yr^{-1}, and 2.2 Tg C yr^{-1}, respectively[3]. Nevertheless, our findings suggest kelp forests could have comparable carbon sequestration benefits to freshwater mineral wetlands (0.8 Tg C yr^{-1})[3] and other BCEs, such as eelgrass meadows (0.2 Tg C yr^{-1}), and tidal marshes (0.8 Tg C yr^{-1}) (Table 1), thus warranting further consideration in Canada's NCS inventories.

We found contrasting patterns of carbon production, storage, and export across Canada's coastlines, reflecting different kelp species assemblages, environmental conditions, and geomorphologies across these vast areas. Notably, the per-area carbon production capacity of Pacific kelp forests exceeded the global averages for subtidal kelps, intertidal seaweeds, subtidal red seaweeds, and floating seaweeds (e.g., *Sargassum* spp)[18]. While the Arctic kelps had the highest total carbon stock and production capacity, due to their extensive coastline and wide continental shelf, the Pacific and Atlantic coasts had a higher total deep ocean export capacity, because of their higher per-area rates of kelp carbon production and hydrological export. However, kelp forests on all three coastlines showed some capacity for export fluxes, suggesting each coast could be incorporated into Canada's NCS inventories.

Our assessment revealed considerable data gaps across all elements of our analysis, underscoring the need for coordinated national kelp monitoring programs. Given the lack of comprehensive maps, we needed to make assumptions about the current extent and maximum depth limit of kelp forests as well as the prevalence of rocky reefs and the occupancy and abundance of kelps across Canada's coastline. We also could not account for ecological drivers (e.g., urchins) that likely limit kelp extents in certain areas[38]. When estimating per-area carbon stocks and production rates, we faced significant data limitations for many kelp species, especially subsurface kelps, leading to large credible confidence intervals for many species. Additionally, we needed to make assumptions about the relative abundance and carbon content of kelp species when extrapolating standing carbon stock, production, and export estimates to the coast-wide scale. Finally, given the complete lack of data on the accumulation of kelp-derived carbon in shelf and deep ocean sinks, we needed to rely on published hydrological export estimates from a published global coastal residence time model[24] to approximate kelp carbon fluxes to the deep ocean (as only one potential pathway of kelp carbon sequestration). A sensitivity analysis revealed that

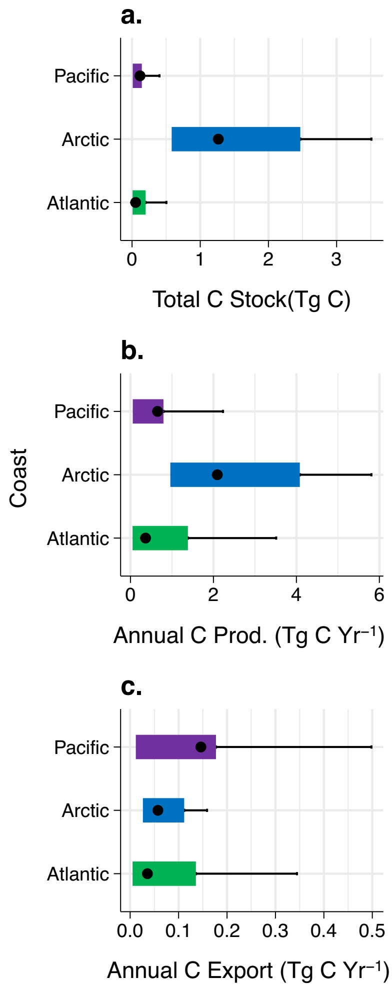

Fig. 4 | National blue carbon capacity of Canadian kelp forests. Panels show the total estimated (**a**) standing carbon stocks (Tg C), **b** carbon production (Tg C yr^{-1}), and (**c**) carbon export (Tg C yr^{1}) capacity of kelp forests. The bars depict the high and low estimates per coast. The circle represents the median estimates for each coast. Error bars show the maximum potential capacity per coast.

the maximum depth limit and the hydrological export rates are likely to have the strongest influence on national estimates (Supplementary Fig. 5–7), suggesting these data should be the highest priority for future research. It is possible that species distribution models accounting for regional differences in the environmental and ecological drivers of kelp extents could help to reduce some of the uncertainty in our assessment. However, given the paucity of datasets more generally, a greater investment in collecting of kelp species abundance, composition, net primary productivity, and relative export data is also needed to estimate kelp carbon sequestration pathways more reliably. Notably, many of these data can be and are already being collected by coastal communities and First Nations in Canada (e.g., through the Marine Plan Partnership program)[39], creating future opportunities for collaborative and indigenous-led research efforts.

While highlighting Canadian kelp forests as a potential asset for enhancing the drawdown of atmospheric CO_2 into ocean carbon sinks, our study has broader implications for developing NCS in other data-limited countries with kelp forests. First, our findings underscore the importance of elucidating and considering the full pathways of carbon production, export, and storage. For example, although Canada's Arctic kelp forests appeared to have the largest blue carbon capacity overall, based on their larger total carbon stocks and production capacities, a more detailed accounting of per-area production and export rates across different coastlines was needed to reveal the larger potential for deep ocean export from Pacific and Atlantic kelp forests. Although it is possible that Arctic and sub-arctic kelp forests play a more important role in carbon burial on the continental shelf, given the wide continental margin, the longer oceanographic residence times, and the greater potential for preservation due to cold temperatures in the Canadian Arctic[36]. Additionally, our findings emphasize the potential importance of spatial and temporal variation in kelp carbon cycling. In Canada, potential export rates varied by an order of magnitude difference (0.9 to 33.6%) depending on the ecoregion[24]. Kelp species also showed considerable variation in their estimated carbon stocks and production rates, which may increase further as more spatially and temporally resolved data becomes available. Overlooking these variables (e.g., species-specific differences; Supplementary Table 6) could lead to biased estimates, potentially undermining the effectiveness of NCS.

Our findings imply that continued environmental changes could have varying consequences for kelp carbon export. Kelp degradation and deforestation have occurred globally due to various anthropogenic stressors and disturbances, including overfishing, eutrophication, climate change, and species invasions[40–44]. For instance, along Canada's Pacific and Atlantic coast, kelp declines have been documented following overgrazing by sea urchins and intensifying marine heatwaves[38,45], while many kelp beds in Atlantic Canada have transitioned to algal turfs due to the combined effects of warming temperatures and interactions with invasive species[41,46,47]. These changes are likely to have severe consequences for associated biodiversity and other ecosystem functions (e.g., fisheries production), and they may also disproportionately reduce the capacity of kelp forests to produce and export carbon.

Variation in the responses of kelp species to climate change may also have important implications for understanding the impacts of kelp species redistribution on carbon sequestration[48]. As kelp distributions are altered by warming temperatures, there could be considerable changes in kelp community composition[49,50]; additionally, more frequent marine heatwaves may lead to local extirpations of kelp species, which could impact carbon production and storage patterns[34,51]. It is possible these changes could lead to enhanced kelp carbon sequestration at the cold edge of species' ranges. For instance, models from the Arctic show the possibility of range expansions for *S. latissima, A. clathratum*, and *A. esculenta* with the loss of sea ice and warming ocean temperatures[52], which could further increase overall carbon production in this region. However, warming ocean temperatures could cause faster decomposition rates[53], and it is unknown whether gains in suitable habitat and productivity would offset the projected losses occurring at the warmer range edges[54] or locally warm hotspots[34,41,55]. Ultimately, expanded monitoring datasets and better forecast models are needed to understand the full scope of climate impacts on kelp carbon sequestration.

Our blueprint provides a valuable roadmap for countries seeking to evaluate the carbon stock, production, and export capacity of their kelp forests. Developed for Canada's extensive coastlines, diverse kelp communities, and complex oceanographic and geomorphologic settings, our approach is useful for evaluating kelp forests wherever there is data on the areal extent, abundance, and net primary productivity of kelp species (see Fig. 1). For coastal countries where comprehensive maps of kelp forests are not yet available, coarse approximations could be obtained using global data on coastal bathymetry and existing global species distribution models[18,51]. Additionally, publicly available data on kelp NPP can be extrapolated from other systems and global models, and used as prior information and data in the absence of regional datasets[56]. In the absence of regional datasets, empirical measurements of kelp carbon export can be supplemented with global ocean transport models, which can help approximate coastal to open ocean transport to various long-term sinks (e.g[23,57].). However, estimates from ocean transport models will still require a thorough interrogation with in-situ experiments and observational studies.

Our integration of Bayesian hierarchical models with extensive data collation and synthesis addresses prevailing challenges associated with estimating species-specific carbon stocks and productivity rates, including data scarcity and the unknown potential for natural variability. One key advantage lies in the ability of Bayesian models to leverage prior information about the known range and variability of kelp productivity from related species and systems when making posterior predictions. Bayesian hierarchical models can also allow for incorporating different forms of measurement error (e.g., standard deviations in field measurements across years) for a more transparent accounting of the residual uncertainty. Furthermore, our approach presents national-scale estimates as a conservative range from a lower bound to a maximum potential as determined by prior information and data. By presenting a range estimate, our approach acknowledges the inherent complexities and variability of kelp ecosystem dynamics, offering a more nuanced assessment. From the perspective of managers and policymakers, this approach is particularly valuable, offering a plausible range of potential outcomes to inform decision-making.

Our analysis highlights three priority research directions to facilitate the incorporation of kelp forests in national NCS inventories. First, our assessment provides first-order estimates of the total annual carbon production capacity of kelp forests, from which the amount of kelp POC predicted to reach deep ocean carbon sinks (i.e., water depths >200 m beyond the continental shelf break) can be estimated. While providing a valuable first step towards estimating kelp carbon sequestration in the deep ocean, the estimates we present likely represent an upper bound for POC export to the deep ocean. In reality, the magnitude of kelp POC that is exported, sequestered, and stored there will depend on a range of factors, including rates of decomposition, vertical exchange, sediment accumulation, resuspension, and the pelagic and benthic processes governing carbon cycling at depths below 200 m—none of which can be reliably assessed from current data sources[20,30,36,58]. Concurrently, our assessment likely underestimates the full carbon sequestration capacity for kelp forests since deep ocean export is just one potential pathway for kelp carbon sequestration[14]. Most of the kelp POC remains within the continental shelf where a small but measurable fraction (approximately 4.6%)[17] becomes buried in shelf sediments, including those of other BCEs; an additional, potentially large, portion of kelp production is converted to recalcitrant DOC[14,24], yet current data is insufficient to quantify these pathways. Improving kelp forest estimates for Canada and other countries will require more granular data on key kelp carbon cycling processes, including rates of POC and DOC production, release, export, retention, and accumulation across different potential reservoirs (i.e., shelf and deep ocean).

Second, significant questions remain about the extent to which kelps can be effectively managed to promote climate change mitigation benefits at national scales[14,26]. To be included in national and international carbon accounting schemes, proposed habitat interventions—including protecting threatened kelp forests and restoring previously lost areas—must demonstrate additionality by resulting in either avoided emissions or enhanced carbon sequestration beyond natural background levels[15]. Yet, the potential for avoided emissions likely varies within and across countries depending on rates of historical and ongoing kelp loss, and the extent to which the main drivers of decline can be managed. Similarly, the capacity to enhance kelp carbon sequestration via restoration depends on the feasibility, rate, and scale of successful kelp recovery. Remote sensing products and habitat distribution models offer promising tools to fill knowledge gaps about relative rates of kelp forest change and recovery, and cumulative impact assessments for coastal marine ecosystems can also provide valuable indicators of potential disturbance risk factors to be addressed[59–61]. Kelp restoration methods are, however, still in their infancy and its not yet clear how quickly restoration efforts can be successfully scaled to meet climate mitigation targets. Further research is needed to quantify and optimize climate mitigation benefits at national scales.

Finally, as we move towards a future characterized by ocean warming and intensifying marine heatwaves, there is a pressing need to understand how these changes could impact the permanence of blue carbon reservoirs associated with kelp forests[15]. Improved forecasting models and expanded monitoring efforts are essential to anticipate changes in kelp carbon sequestration and to develop climate-smart management[53]. Integrating kelp forests into national and global climate change mitigation strategies also requires robust and standardized methodologies for quantifying and verifying changes in carbon stocks and fluxes to ocean carbon sinks under future scenarios[62].

As nations strive to meet their net zero targets for greenhouse gas emissions, incorporating kelp forests into NCS inventories represents an important step in harnessing the full potential of ocean ecosystems. To that end, countries must be able to reliably estimate and predict changes in kelp carbon sequestration resulting from proposed management, conservation, and restoration actions. Our analytical framework offers a blueprint for evaluating the carbon stock, production, and export capacity of kelp forests, as critical precursors to assessing changes sequestration. Kelp forests cannot yet be fully accounted for in NCS inventories because of the data gaps and uncertainties we outline. However, the magnitude of kelp carbon export we estimate for Canada suggests kelp forests do merit further consideration in national inventories and that they could be accounted for in future as the priority research gaps we outline are addressed. In the meantime, we advocate for a precautionary approach to avoid further kelp declines that could compromise their role in ocean carbon sequestration pathways. In the face of uncertainty, precautionary protection paired with targeted research offers the best path forward towards realizing the climate mitigation benefits of kelp forests and other BCEs.

Methods

Study area

Our study area spans the Pacific, Arctic, and Atlantic coasts of Canada, from mean sea level out to the 20-meter depth contour. In the Pacific, this includes 25,000 km of coastline from 48 to 55° N; in the Arctic, 162,000 km from 51 to 83° N; and in the Atlantic, 42,000 km from 43 to 60° N. These coasts support a diversity of kelp forest-forming species. Indeed, the Northeast Pacific Ocean is considered the evolutionary center of origin for kelps[63] and includes >30 kelp species that vary in morphology and ecological niche[64]. The Arctic and North Atlantic oceans were subsequently colonized repeatedly following glaciation events and are now home to >10 kelp species[65,66].

Data scoping

We collated information and datasets from a variety of published and unpublished sources on the areal extent, biomass, plant density, canopy cover, and NPP of the most common kelp forest species (Supplementary Table 1). We limited our search to surface and subsurface kelp species found in the subtidal zone of at least one Canadian coast, according to global species-occurrence databases[19,67]. Given that many kelp species in Canada are annuals, reaching peak growth rates and stages of development during the summer months (i.e., May to August in the northern hemisphere) we limited our search to survey datasets collected during these months, when kelp forests are likely to achieve their highest standing biomass and primary productivity rates[68]. To collate sources from the published literature, we used an existing database of macroalgal NPP measurements compiled from a combination of reports, peer-reviewed studies, and PhD and master's theses published between 1967 and 2021[56,69]. Following similar search criteria, we expanded this NPP database to include additional papers published between 2021–2023 for Canadian kelp species. We then used this updated NPP database to compile published measurements of kelp biomass from the text, figures, and supplementary datasets of the original source material. In addition, we compiled datasets from unpublished sources using a snowball search method, where we reached out to the authors of previously published kelp papers in Canada and asked for recommendations on potential data sources for kelp extent, biomass, canopy cover, and net primary productivity.

We focused subsequent analyses on the kelp species that had at least one biomass and NPP record on a given coast (Supplementary Table 2). These included the two surface kelp species (i.e., *Macrocystis pyrifera* and *Nereocystis luetkeana*) and seven of the 15 subsurface kelps found on the Pacific coast (*i.e., Agarum clathratum, Costaria costata*, *Hedophyllum nigripes*, *Neoagarum fimbriatum, Pterygophora californica, Pleurophycus gardneri, Saccharina latissima*); five of the seven species found on the Arctic coast (i.e., *A. clathratum, Laminaria digitata, L. solidungula, H. nigripes*, and *S. latissima*; all subsurface); and three of the five species found on the Atlantic coast (*i.e., A. clathratum, L. digitata*, and *S. latissima*; all subsurface). Since *H. nigripes* could not be differentiated from *L. digitata* in some of the Arctic and Atlantic data records, the two species were grouped together in subsequent analyses. Likewise, we grouped *A. clathratum* and *N. fimbriatum* records due to the difficulties with differentiating these two species in situ.

Lastly, we collated information and datasets that could be used to estimate the amount of kelp-derived carbon entering the three main pathways for carbon sequestration: (1) refractory DOC pools, (2) shelf burial, and (3) deep ocean export (Supplementary Table 3). However, because there was not enough data to evaluate the first two pathways, we focused subsequent analyses on the deep ocean export pathway.

Determining the potential extent of kelp forests

Subsurface kelps. We produced maximum, high, and low estimates of the potential areal extent of subsurface kelp forest in Canada using available depth, substrate, and kelp percent cover data. As a hypothetical maximum potential extent for subsurface kelps, we calculated the area of suitable rocky seafloor across Canada, i.e., the areal extent of rocky seafloor between mean low water and the 20 m depth contour in millions of hectares (Mha)[51]. This is a conservative depth cutoff since kelp forests occur deeper (50 m) in some areas[70]. Depth estimates were based on the General Bathymetric Chart of the Ocean data (https://www.gebco.net; GEBCO)—a gridded global terrain model for the ocean and land at 15-arc-second resolution. The extent of rocky seafloor was based on public spatial data repositories for the Pacific and Atlantic coasts[71,72]. Since there was limited information on the distribution of rocky seafloor for most of the Atlantic coast, we used the fraction of rocky seafloor found on the Scotian shelf (30.7%) as a conservative proxy[71]. For the Arctic, we used the fraction of rocky seafloor used by previous global studies (20%)[18]. Finally, we masked extents in the Arctic by the areal coverage of perennial sea ice occurring at the northern edges, using spatial data layers from BioOracle[73].

To provide more constrained high and low bound estimates for the potential extent of subsurface kelp forests, we combined the maximum potential extent maps with existing field surveys of the percent cover of kelp forests from the Pacific, Atlantic, and Arctic coasts. We acquired quadrat surveys of the percent cover of subsurface kelp species from active monitoring programs[74] and the peer-reviewed literature (Supplementary Table 1). To calculate the high estimate, we multiplied the maximum potential extent by the 75th percentile of observed percent cover for all kelp species (regardless of the species composition) on each coast. Additionally, we calculated the low estimate as the maximum potential area multiplied by the 25th percentile of observed kelp cover.

Surface kelps. We also produced maximum, high, and low bound estimates for the potential areal extent of surface kelp forests, as a special case found solely on the Pacific coast of Canada. These estimates were based on three different data sources, representing a range of plausible extent estimates for canopy-forming kelp. First, we defined the maximum potential extent as the area of all suitable rocky seafloor above 10 m water depth—based on the depth distribution of 90% of the bull kelp (*Nereocystis luetkeana*) and giant kelps (*Macrocystis pyrifera*) observations we collated for British Columbia (Supplementary Fig. 4). To produce high and low estimates for surface kelps, we used two distinct data sources. For the high estimate, we used available shoreline maps of the historical distribution of *M. pyrifera* and *N. luetkeana* compiled by the British Columbia Shore Zone program[75,76]. This dataset provides a comprehensive inventory of shoreline biota, including kelp presence, based on oblique aerial surveys conducted between 2004 and 2007. From this data, we estimated the historical extent of surface kelps as the intersection between shoreline detections (i.e., within 500 m) and the maximum area of suitable rocky seafloor adjacent to the shoreline, assuming that all adjacent rocky reef was occupied at the time of survey. For the low estimate, we acquired global distribution maps of surface canopy kelps determined from classified 20 m resolution Sentinel-2 satellite imagery, representing the average detection of surface kelps between 2015 to 2019[77]. Even when collected at a similar time-period, this latter dataset is likely to yield smaller estimates given its high resolution and conservative assumptions. However, this data was also collected after a major heatwave event, after which substantial declines in surface kelps were observed[55]. Thus, it provides a more constrained low estimate for surface kelps. We validated both datasets through expert comparison with Google Earth Imagery, removing obvious false positives found in higher estuaries and along the intertidal zone, in ArcGIS Pro Version. 3.0.

Determining the per-area carbon stocks of kelp species

We quantified carbon standing stocks associated with kelp forests in Canada by compiling available data on the area-specific biomass and plant density of kelp species from published and unpublished sources (Supplementary Table 1). Wet weight measurements (i.e., g WW m^{-2}) for each species and coast were converted to dry weight (g DW m^{-2}) using species- and coast-specific conversions from the peer-reviewed literature[56]. Kelp densities (i.e., number m^{-2}) for each species and coast were also converted to dry weight using available average individual wet weight measurements[56]. When carbon content measurements were not already available, we used previously published species- and coast-specific ratios to convert dry weight measurements to the area-specific organic carbon content (g C m^{-2}) of each sample[56]. Finally, we converted all measurements of organic carbon content to carbon standing stocks in units of megagrams per hectare (Mg ha^{-1}) by species.

Determining the per-area annual carbon production rates of kelp species

We used available published and unpublished measurements of net primary productivity for all kelp species found in Canadian waters (Supplementary Table 1)[56,69]. We also used published net primary productivity records from locations with similar environmental conditions to Canadian waters (i.e., within the range of mean ocean temperatures observed on the Pacific, Arctic, and/or Atlantic coasts according to BioOracle v. 2 data layers)[73]. All wet weights were converted to dry weight measurements, and then all dry measurements were converted to area-specific rates of net primary productivity (i.e., g C m^{-2} yr^{-1}), using species- and coast-specific conversions from the literature[56]. We then converted all measurements of NPP to annual carbon production in units of megagrams per hectare per year (Mg ha^{-1} Yr^{-1}) by species.

Bayesian hierarchical models

We used Bayesian hierarchical models to evaluate the potential for natural variation in the per-area carbon stocks (Mg C ha^{-1}) and carbon production rates (Mg C ha^{-1} yr^{-1}) of different kelp species in Canada. Bayesian hierarchical models are parameterized similarly to hierarchical linear regression models using the Stan computational framework (http://mc-stan.org/), which can be accessed via the 'brms' package of the R programming language (version 2022.12)[78]. A key advantage of Bayesian hierarchical models is the ability to generate a posterior distribution, representing the central tendency (i.e., the posterior mean) and the probabilistic range of uncertainty surrounding a parameter estimate. A credible confidence interval (CCI) can be derived from this posterior distribution, indicating the range within which the true parameter value is likely to fall. Additionally, the 'brms' package allows for the explicit consideration of measurements of standard deviation as an additional response term, allowing for adjusted CCIs that reflect greater uncertainty where there is greater variability in kelp biomass and NPP. Finally, a Bayesian approach allows for the use of informative priors based on observations from different systems that further constrain the parameter estimates and CCIs. Additional information about using the R package "brms" can be found in the literature and the documentation[78,79]. Scripts for model parameterization, selecting informative priors, and evaluating model outputs can also be found in our Github repository (https://

github.com/jennmchenry1/A-blueprint-for-national-assessments-of-blue-carbon-capacity-of-kelp-forests-CA).

The observed carbon standing stocks and production rates of eleven kelp species were modeled as the response variables. To account for measurement uncertainty in the available observations, we included the standard deviation measurements representing the site-level variation as an additional response term. For each species, we built sets of competing models that tested the effects of different combinations of predictors on species carbon stocks and production rates (Supplementary Table 7). We accounted for potential fixed effects of mean annual sea surface temperatures derived BioOracle[73] and the oceanic context (i.e., Pacific, Arctic, and Atlantic), and controlled for the sampling year and site identity as random effects. The models ran for 5000 iterations with 2500 warm-ups using three chains. Convergence was visually assessed by examining the trace plots and further verifying all coefficients achieving an Rhat value of 1[80]. To determine which model best described each response variable, we used an approximation for leave-one-out (LOO) cross-validation ('loo' package)[81,82]. We evaluated the performance of the final models through a series of posterior predictive checks where draws from the posterior distribution of model parameters were compared to the observed data as a measure of model goodness of fit (Supplementary Fig. 8–9).

Models were trained with weakly informative 'priors', setting the scale of the prior distribution to be larger than and consistent with the range of potential observed values in our collated response datasets (Supplementary Table 8) and the range of global synthesized primary productivity measurements from macroalgal forests[69]. To ensure that our choice of priors did not overly constrain the resulting posterior predictions or inflate the uncertainty intervals, we conducted a prior sensitivity analysis for the three most data rich species in our dataset (i.e., *M. pyrifera, N. leutkeana*, and *S. latissima*) and used the best matched set of priors for the remaining species.

We present the final models for eleven kelp species, which were selected by the approximate LOO cross-validation (Supplementary Table 9). The final models were used to generate posterior mean estimates of the potential carbon stocks and production rates associated with kelp species, including the 90% credible confidence intervals around those estimates. Significant differences among the posterior mean estimates were assessed through the comparison of the percent overlap between credible confidence intervals.

Estimating the national blue carbon capacity of kelp forests

We estimated the total carbon stock capacity (Tg C) of current kelp forests in Canada as the summed product of the kelp forest extent (E_{coast}) and the carbon stock potential of kelp forests across Canada's three coastlines ($CStock_{coast}$) (1). As inputs to this calculation, we used the posterior mean estimates of the per-area carbon stocks of individual kelp species (described above). To account for the fact that kelps often persist in multi-species assemblages and thus are not likely to persist at their maximum biomass potential, we estimated the per-area carbon stock of kelp forests per coast ($CStock_{coast}$) as the summation of the posterior mean estimates for each kelp species ($CStock_{spp}$), weighted by the relative abundance of that kelp species (A_{spp}), on each coast. We used the maximum, high, and low kelp forest extent estimates as inputs to determine the most likely maximum, high, and low carbon stock capacity of each coast.

$$\begin{aligned}
&\text{Carbon Stock of Kelp Forests Per} - \text{area}\left(\text{CStock}_{\text{coast}}\right)\\
&\text{CStock}_{\text{coast}} = \sum\left(\text{CStock}_{\text{spp1}} \times \text{A}_{\text{spp1}}\right) + \left(\text{CStock}_{\text{spp2}} \times \text{A}_{\text{spp1}}\right) + \ldots\\
&\qquad + \left(\text{CStock}_{\text{sppN}} \times \text{A}_{\text{sppN}}\right)\\
&\text{Total Standing Carbon Stock of Kelp Forests}\left(\text{CStock}_{\text{total}}\right)\\
&\text{CStock}_{\text{total}} = \sum\left(\text{E}_{\text{coast1}} \times \text{CStock}_{\text{coast1}}\right) + \left(\text{E}_{\text{coast2}} \times \text{CStock}_{\text{coast2}}\right) + \ldots\\
&\qquad + \left(\text{E}_{\text{coastN}} * \text{CStock}_{\text{coastN}}\right)
\end{aligned} \tag{1}$$

Additionally, we estimated the total annual carbon production capacity (Tg C yr^{-1}) of current kelp forests in Canada as the summed product of the kelp forest extent (E_{coast}) and the carbon production rate of kelp forests across Canada's three coastlines ($CProd_{coast}$) (2). To estimate the per-area carbon production rate of kelp forests per coast ($CProd_{coast}$), we summed the posterior mean estimates for each kelp species ($CProd_{spp}$), weighted by the relative abundance of that kelp species (A_{spp}), on each coast. We calculated the total carbon production capacity of kelp forests per coast in terms of the maximum, high bound, and lower extent estimates.

$$\begin{aligned}
&\text{Carbon Production of Kelp Forests Per} - \text{area}\left(\text{CProd}_{\text{coast}}\right)\\
&\text{CProd}_{\text{coast}} = \sum\left(\text{CProd}_{\text{spp1}} \times \text{A}_{\text{spp1}}\right) + \left(\text{CProd}_{\text{spp1}} \times \text{A}_{\text{spp1}}\right) + \ldots\\
&\qquad + \left(\text{CProd}_{\text{spp1}} \times \text{A}_{\text{sppN}}\right)\\
&\text{Total Standing Carbon Production of Kelp Forests}\left(\text{CProd}_{\text{total}}\right)\\
&\text{CProd}_{\text{total}} = \sum\left(\text{E}_{\text{coast1}} \times \text{CProd}_{\text{coast1}}\right) + \left(\text{E}_{\text{coast2}} \times \text{CProd}_{\text{coast2}}\right) + \ldots\\
&\qquad + \left(\text{E}_{\text{coastN}} * \text{CProd}_{\text{coastN}}\right)
\end{aligned} \tag{2}$$

Finally, we estimated the total annual capacity (Tg C yr^{-1}) for carbon export fluxes from Canada's kelp forests to deep waters beyond the continental shelf break (i.e., the 200 m isobath), as a necessary precursor for carbon sequestration in the deep ocean. We determined the total annual export capacity of kelp forests in Canada as the summed product of the estimated kelp forest extent (E_{coast}) and the annual carbon export flux potential (or the magnitude of kelp carbon reaching the shelf break in Mg C yr^{-1}) from kelp forests across Canada's three coastlines ($CFlux_{coast}$) (3). As inputs to this calculation, we used published estimates of the carbon export rate—or the fraction of kelp detrital material—that is transported from the coastal domain to beyond the shelf break within Canada's 14 marine ecoregions (Supplementary Table 3)[24]. These measurements are based on empirical data on seaweed decomposition rates and a global model of coastal residence time, which calculates the amount of time a water mass remains within the coastal environment before being transported to the open ocean to waters deeper than 200 m from all 232 marine ecoregions of the world (regions previously defined by Spalding et al.[83]). A full description of the methods can be found in Filbee-Dexter et al.[24]. From this global model, we determined the average carbon export rate for each of Canada's three coasts (Exp_{coast}). To estimate the carbon export flux potential from kelp forests on each coast ($CFlux_{coast}$), we multiplied the average carbon export rate (Exp_{coast}) by the annual per-area carbon production rate of kelp forests for a given coast ($CProd_{coast}$; calculated above). Finally, we calculated the total carbon export capacity of kelp forests per coast in terms of the maximum, high, and lower extent estimates.

$$\begin{aligned}
&\text{Annual Export of Kelp Carbon to the Deep Ocean Per} - \text{Area}\left(\text{CFlux}_{\text{coast}}\right)\\
&\text{CFlux}_{\text{coastN}} = \text{CProd}_{\text{coastN}} \times \text{Exp}_{\text{coastN}}\\
&\text{Total Annual Export of Kelp Carbon to the Deep Ocean}\left(\text{CFlux}_{\text{total}}\right)\\
&\text{CFlux}_{\text{total}} = \sum\left(\text{E}_{\text{coast1}} \times \text{CFlux}_{\text{coast1}}\right) + \left(\text{E}_{\text{coast2}} \times \text{CFlux}_{\text{coast2}}\right) + \ldots\\
&\qquad + \left(\text{E}_{\text{coastN}} * \text{CFlux}_{\text{coastN}}\right)
\end{aligned} \tag{3}$$

Data availability

All research outputs, including collated and synthesized datasets, blueprint documents, templates, and R code, can be found in the Blue Carbon Canada dataverse on Borealis (https://doi.org/10.5683/SP3/DLFO4M). Additionally, a copy of all research outputs can be found in Github repository (https://github.com/jennmchenry1/A-blueprint-for-national-assessments-of-blue-carbon-capacity-of-kelp-forests-CA).

Received: 13 September 2024; Accepted: 28 April 2025;
Published online: 04 June 2025

References

1. Griscom, B. W. et al. Natural climate solutions. *Proc. Natl. Acad. Sci.* **114**, 11645–11650 (2017).
2. Macreadie, P. I. et al. Blue carbon as a natural climate solution. *Nat. Rev. Earth Environ.* **2**, 826–839 (2021).

3. Drever, C. R. et al. Natural climate solutions for Canada. *Sci. Adv.* **7**, eabd6034 (2021).
4. Fargione, J. E. et al. Natural climate solutions for the United States. *Sci. Adv.* **4**, eaat1869 (2018).
5. Alongi, D. M. Global significance of mangrove blue carbon in climate change mitigation. *Sci* **2**, 67 (2020).
6. Chmura, G. L., Anisfeld, S. C., Cahoon, D. R. & Lynch, J. C. Global carbon sequestration in tidal, saline wetland soils. *Glob. Biogeochem. Cycles* **17**, (2003).
7. Fourqurean, J. W. et al. Seagrass ecosystems as a globally significant carbon stock. *Nat. Geosci.* **5**, 505–509 (2012).
8. Mcleod, E. et al. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Front. Ecol. Environ.* **9**, 552–560 (2011).
9. Bufarale, G. & Collins, L. B. Stratigraphic architecture and evolution of a barrier seagrass bank in the mid-late Holocene, Shark Bay, Australia. *Mar. Geol.* **359**, 1–21 (2015).
10. Duarte, C. M., Middelburg, J. J. & Caraco, N. Major role of marine vegetation on the oceanic carbon cycle. *Biogeosciences* **2**, 1–8 (2005).
11. Lo Iacono, C. et al. Very high-resolution seismo-acoustic imaging of seagrass meadows (Mediterranean Sea): Implications for carbon sink estimates. *Geophys. Res. Lett*. **35**, (2008).
12. Waycott, M. et al. Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *Proc. Natl. Acad. Sci.* **106**, 12377–12381 (2009).
13. Macreadie, P. I. et al. Can we manage coastal ecosystems to sequester more blue carbon? *Front. Ecol. Environ.* **15**, 206–213 (2017).
14. Pessarrodona, A. et al. Carbon sequestration and climate change mitigation using macroalgae: a state of knowledge review. *Biol. Rev*. brv.12990 https://doi.org/10.1111/brv.12990 (2023).
15. Vanderklift, M. A. et al. A guide to international climate mitigation policy and finance frameworks relevant to the protection and restoration of blue carbon ecosystems. *Front. Mar. Sci.* **9**, 872064 (2022).
16. Howard, J. et al. Blue carbon pathways for climate mitigation: Known, emerging and unlikely. *Mar. Policy* **156**, 105788 (2023).
17. Krause-Jensen, D. & Duarte, C. M. Substantial role of macroalgae in marine carbon sequestration. *Nat. Geosci.* **9**, 737–742 (2016).
18. Duarte, C. M. et al. Global estimates of the extent and production of macroalgal forests. *Glob. Ecol. Biogeogr.* **31**, 1422–1439 (2022).
19. Jayathilake, D. R. M. & Costello, M. J. A modelled global distribution of the kelp biome. *Biol. Conserv*. **252**, 108815 (2020).
20. Pedersen, M. F. et al. Detrital carbon production and export in high latitude kelp forests. *Oecologia* **192**, 227–239 (2020).
21. Ortega, A. et al. Important contribution of macroalgae to oceanic carbon sequestration. *Nat. Geosci.* **12**, 748–754 (2019).
22. Filbee-Dexter, K., Wernberg, T., Norderhaug, K. M., Ramirez-Llodra, E. & Pedersen, M. F. Movement of pulsed resource subsidies from kelp forests to deep fjords. *Oecologia* **187**, 291–304 (2018).
23. Queirós, A. M. et al. Identifying and protecting macroalgae detritus sinks toward climate change mitigation. *Ecol. Appl.* **33**, e2798 (2023).
24. Filbee-Dexter, K. et al. Carbon export from seaweed forests to deep ocean sinks. *Nat. Geosci*. **17**, 552–559 (2024).
25. Krumhansl, K. & Scheibling, R. Production and fate of kelp detritus. *Mar. Ecol. Prog. Ser.* **467**, 281–302 (2012).
26. Hurd, C. L. et al. Forensic carbon accounting: Assessing the role of seaweeds for carbon sequestration. *J. Phycol.* **58**, 347–363 (2022).
27. Paine, E. R., Schmid, M., Boyd, P. W., Diaz-Pulido, G. & Hurd, C. L. Rate and fate of dissolved organic carbon release by seaweeds: a missing link in the coastal ocean carbon cycle. *J. Phycol.* **57**, 1375–1391 (2021).
28. Geraldi, N. R. et al. Fingerprinting blue carbon: rationale and tools to determine the source of organic carbon in marine depositional environments. *Front. Mar. Sci*. **263**, 6–23 (2019).
29. Krause-Jensen, D. et al. Sequestration of macroalgal carbon: the elephant in the blue carbon room. *Biol. Lett.* **14**, 20180236 (2018).
30. Queirós, A. M. et al. Connected macroalgal-sediment systems: blue carbon and food webs in the deep coastal ocean. *Ecol. Monogr*. **89**, e01366 (2019).
31. Fujita, R. et al. Seaweed blue carbon: Ready? Or Not? *Mar. Policy* **155**, 105747 (2023).
32. Araya-Lopez, R., de Paula Costa, M. D., Wartman, M. & Macreadie, P. I. Trends in the application of remote sensing in blue carbon science. *Ecol. Evol.* **13**, e10559 (2023).
33. Krumhansl, K. A. et al. Global patterns of kelp forest change over the past half-century. *Proc. Natl. Acad. Sci.* **113**, 13785–13790 (2016).
34. Mora-Soto, A. et al. Environmental characteristics and floating kelp dynamics in the southern Salish Sea, British Columbia, Canada. *Front. Mar. Sci*. **11**, (2024).
35. Archambault, P. et al. From sea to sea: Canada's three oceans of biodiversity. *PLoS One* **5**, e12182 (2010).
36. Filbee-Dexter, K. et al. Ocean temperature controls kelp decomposition and carbon sink potential. *PLOS Biol*. **20**, e3001702 (2020).
37. Ross, F. W. et al. A preliminary estimate of the contribution of coastal blue carbon to climate change mitigation in New Zealand. *N. Z. J. Mar. Freshw. Res*. **58**, 1–11 (2023).
38. Filbee-Dexter, K. & Scheibling, R. E. Sea urchin barrens as alternative stable states of collapsed kelp ecosystems. *Mar. Ecol. Prog. Ser.* **495**, 1–25 (2014).
39. Thompson, M. MaPP Kelp Monitoring Protocol. Marine Plan Partnership for the North Pacific Coast (MAPP), MPPFTNPC (2021).
40. Connell, S. D. et al. Recovering a lost baseline: missing kelp forests from a metropolitan coast. *Mar. Ecol. Prog. Ser.* **360**, 63–72 (2008).
41. Filbee-Dexter, K., Feehan, C. & Scheibling, R. Large-scale degradation of a kelp ecosystem in an ocean warming hotspot. *Mar. Ecol. Prog. Ser.* **543**, 141–152 (2016).
42. Johnson, C. R. et al. Climate change cascades: Shifts in oceanography, species' ranges and subtidal marine community dynamics in eastern Tasmania. *J. Exp. Mar. Biol. Ecol.* **400**, 17–32 (2011).
43. Steneck, R. S. et al. Kelp forest ecosystems: biodiversity, stability, resilience and future. *Environ. Conserv.* **29**, 436–459 (2002).
44. Wernberg, T. et al. An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. *Nat. Clim. Change* **3**, 78–82 (2013).
45. Starko, S. et al. Microclimate predicts kelp forest extinction in the face of direct and indirect marine heatwave effects. *Ecol. Appl*. **32**, e2673 (2022).
46. Steneck, R. S., Leland, A., McNaught, D. C. & Vavrinec, J. Ecosystem flips, locks, and feedbacks: the lasting effects of fisheries on Maine's kelp forest ecosystem. *Bull. Mar. Sci.* **89**, 31–55 (2013).
47. Attridge, C. M., Metaxas, A. & Denley, D. Wave exposure affects the persistence of kelp beds amidst outbreaks of the invasive bryozoan Membranipora membranacea. *Mar. Ecol. Prog. Ser.* **702**, 39–56 (2022).
48. Oliver, E. C. et al. Projected marine heatwaves in the 21st century and the potential for ecological impact. *Front. Mar. Sci.* **6**, 734 (2019).
49. Assis, J., Araújo, M. B. & Serrão, E. A. Projected climate changes threaten ancient refugia of kelp forests in the North Atlantic. *Glob. Change Biol.* **24**, e55–e66 (2018).
50. Jueterbock, A. et al. Climate change impact on seaweed meadow distribution in the North Atlantic rocky intertidal. *Ecol. Evol.* **3**, 1356–1373 (2013).
51. Filbee-Dexter, K. & Wernberg, T. Substantial blue carbon in overlooked Australian kelp forests. *Sci. Rep.* **10**, 12341 (2020).
52. Goldsmit, J. et al. Kelp in the Eastern Canadian Arctic: Current and future predictions of habitat suitability and cover. *Front. Mar. Sci.* **18**, 742209 (2021).
53. Wright, L., Pessarrodona, A. & Foggo, A. Climate-driven shifts in kelp forest composition reduce carbon sequestration potential. *Glob. Change Biol*. **20**, 5514–5531 (2022).

54. Filbee-Dexter, K., Wernberg, T., Fredriksen, S., Norderhaug, K. M. & Pedersen, M. F. Arctic kelp forests: Diversity, resilience and future. *Glob. Planet. Change* **172**, 1–14 (2019).
55. Starko, S. et al. Local and regional variation in kelp loss and stability across coastal British Columbia. *Mar. Ecol. Prog. Ser*. **733**, 1–26 (2024).
56. Pessarrodona, A., Filbee-Dexter, K., Krumhansl, K. A., Moore, P. J. & Wernberg, T. A global dataset of seaweed net primary productivity. *Sci. Data* https://doi.org/10.1101/2021.07.12.452112 (2022).
57. Filbee-Dexter, K. et al. Seaweed forests are carbon sinks that can mitigate CO_2 emissions: a comment on Gallagher et al. (2022). *ICES J. Mar. Sci.* **80**, 1814–1819 (2023).
58. Leithold, E. L., Blair, N. E. & Wegmann, K. W. Source-to-sink sedimentary systems and global carbon burial: A river runs through it. *Earth-Sci. Rev.* **153**, 30–42 (2016).
59. Murray, C. C., Kelly, N. E., Nelson, J. C., Murphy, G. E. P., & Agbayani, S. *Cumulative Impact Mapping and Vulnerability of Canadian Marine Ecosystems to Anthropogenic Activities and Stressors*. vi + 46 https://waves-vagues.dfo-mpo.gc.ca/library-bibliotheque/41251556.pdf (2024).
60. Singh, G. G. et al. Mapping cumulative impacts to coastal ecosystem services in British Columbia. *PLOS ONE* **15**, e0220092 (2020).
61. Halpern, B. S. et al. Recent pace of change in human impact on the world's ocean. *Sci. Rep.* **9**, 11609 (2019).
62. Needelman, B. A. et al. The science and policy of the verified carbon standard methodology for tidal wetland and seagrass restoration. *Estuaries Coasts* **41**, 2159–2171 (2018).
63. Starko, S. et al. A comprehensive kelp phylogeny sheds light on the evolution of an ecosystem. *Mol. Phylogenet. Evol.* **136**, 138–150 (2019).
64. Druehl, L. D. The pattern of Laminariales distribution in the northeast Pacific. *Phycologia* **9**, 237–247 (1970).
65. Bringloe, T. T., Verbruggen, H. & Saunders, G. W. Population structure in Arctic marine forests is shaped by diverse recolonisation pathways and far northern glacial refugia. *PNAS.* **117**, 22590–22596 (2020).
66. Bolton, J. J. The biogeography of kelps (Laminariales, Phaeophyceae): a global analysis with new insights from recent advances in molecular phylogenetics. *Helgol. Mar. Res.* **64**, 263–279 (2010).
67. Assis, J. et al. A fine-tuned global distribution dataset of marine forests. *Sci. Data* **7**, 119 (2020).
68. Wheeler, W. N. & Druehl, L. D. Seasonal growth and productivity of *Macrocystis integrifolia* in British Columbia, Canada. *Mar. Biol.* **90**, 181–186 (1986).
69. Pessarrodona, A. et al. Global seaweed productivity. *Sci. Adv.* **8**, eabn2465 (2022).
70. Castro de la Guardia, L. et al. Increasing depth distribution of Arctic kelp with increasing number of open water days with light. *Elem Sci Anth* **11**, 00051 (2023).
71. Greenlaw, M. & Harvey, C. Data of: A substrate classification for the Inshore Scotian Shelf and Bay of Fundy, Maritimes Region. *Coastal Ecosystems Science Division, Fisheries and Oceans Canada, St. Andrews, N.B*. (2022).
72. Gregr, E. J., Haggarty, D. R., Davies, S. C., Fields, C. & Lessard, J. Comprehensive marine substrate classification applied to Canada's Pacific shelf. *PLOS ONE* **16**, e0259156 (2021).
73. Assis, J. et al. Bio-ORACLE v2. 0: Extending marine data layers for bioclimatic modelling. *Glob. Ecol. Biogeogr*. **27**, 277–284 (2018).
74. Lessard, J. DFO Dive surveys of algae and substrate in British Columbia. Government of Canada; Fisheries and Oceans Canada (DFO); Pacific Science; Ecosystem Science Division. https://open.canada.ca/data/en/dataset/3478f0c4-d143-4f3c-a9e2-7fe8455a639e (2023).
75. British Columbia Shore Zone Data Portal. https://soggy2.zoology.ubc.ca/geonetwork/srv/eng/catalog.search#/metadata/501b77d2-573c-44d9-ac92-140d0f024e44 (2022).
76. Howes, D., Harper, J. & Owens, E. Physical shore-zone mapping system for British Columbia. *Rep. Prep. Environ. Emerg. Serv. Minist. Environ. Vic. BC Coast. Ocean Resour. IncSidney BC Owens Coast. Consult. Bainbridge WA* (1994).
77. Mora-Soto, A. et al. A high-resolution global map of giant kelp (*Macrocystis pyrifera*) forests and intertidal green algae (*Ulvophyceae*) with Sentinel-2 imagery. *Remote Sens* **12**, 694 (2020).
78. Bürkner, P. brms: An R Package for Bayesian Multilevel Models Using Stan. *J Stat. Softw.* **80**, 1-28 (2017).
79. Barreda, S. & Silbert, N. Fitting Bayesian regression models with brms. In *Bayesian Multilevel Models for Repeated Measures Data* 55–86 (Routledge, 2023).
80. Gelman, A. Parameterization and Bayesian modeling. *J. Am. Stat. Assoc.* **99**, 537–545 (2004).
81. Vehtari, A., Gelman, A. & Gabry, J. Practical Bayesian model evaluation using leave-one-out cross-validation and WAIC. *Stat. Comput.* **27**, 1413–1432 (2017).
82. Vehtari, A. et al. loo: Efficient leave-one-out cross-validation and WAIC for Bayesian models. R package version 2.5.1. https://mc-stan.org/loo (2022).
83. Spalding, M. D. et al. Marine ecoregions of the world: a bioregionalization of coastal and shelf areas. *AIBS Bull* **57**, 573–583 (2007).

Acknowledgements

We gratefully acknowledge funding and research support from Fisheries and Oceans Canada (*contract number: 6861*), the Natural Sciences and Engineering Research Council of Canada's (NSERC) Alliance grant program (*grant number: ALLRP 571068-21*), and the Mitacs Accelerate grant program (*grant number: IT28407*). This work is publication no. 5 of Blue Carbon Canada. We also acknowledge co-author funding from The Tula Foundation, The Hakai Institute, ArcticNet (*ArcticKelp P101*) and the Australian Research Council (*grant number: DP220100650*).

Author contributions

J.M. and J.K.B. conceived and designed the study. J.M. acquired and collated the data with assistance from B.T. and input from K.F.D., K.A.K., K.M., M.H.L., P.A., C.A, D.C., M.Co., M.Cs, D.K.O., L.J., J.L., A.M., A.M.S., C.K.N., O.P., L.R., S.S., J.Y., and J.K.B. J.M. conducted the analysis with significant input from D.K.O., K.A.K., K.F.D., and J.K.B. J.M. wrote the manuscript with significant contributions from J.K.B., and revisions and input from D.K.O., K.F.D., K.A.K., K.M., M.H.L., P.A., C.A, D.C., M.Co., M.Cs, L.J., J.L., A.M.S., A.M., O.P., C.K.N., L.R., S.S., and J.Y.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s44183-025-00125-6.

Correspondence and requests for materials should be addressed to Jennifer McHenry.