



Quantifying carbon footprint for ecological river restoration

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Abstract

RIVER restoration is a popular technique to rehabilitate degraded river habitat. Given the nature of these types of engineering projects, using ecological indicators to monitor the restoration effectiveness has been a traditional approach. However, as this approach emphasizes the post-project performance, environmental impact attributed to a project's construction phase has received little attention directly or indirectly. This study quantified the carbon footprint of ecological river restoration, using a project in California as a case study. A topographic diversity index (TDI) was developed as a functional unit of the river restoration project, indicating how a restoration project can increase the variation of habitat topography. The results show that river restoration can lead to greenhouse gas emissions ranging from 288 to 336 kg CO₂ equivalent (kg CO₂e) for every 1% of TDI improvement, or 9–14 kg CO₂e per meter stream restored. This study identified that improving raw material acquisition plans and heavy-duty equipment rental decision can be feasible strategies leading to the reduction of carbon footprint.

Keywords Life-cycle assessment · Environmental impact · Carbon footprint · Topographic diversity index · River restoration · Habitat improvement

1 Introduction

Freshwater ecosystems around the world have been degraded, damaged, or destroyed by human activities such as agricultural expansion, urbanization, industrialization, and damming and channelization (Vörösmarty et al., 2010). In the US, 46% of rivers and streams were in poor biological condition in 2009 with excess levels of nutrients, unhealthy

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shoreline vegetation, and high degrees of riparian disturbance (EPA, 2013). Concomitant with river ecosystem degradation declines in river biodiversity and ecosystem services (Vaughn, 2010), which has also contributed to substantial economic loss related to fishing, recreation, and real estate (Dodds et al., 2009).

Given the importance of river ecosystems and the severity of environmental degradation, there have been growing interests in ecological river restoration in the US (Roy et al., 2018; Wohl et al., 2015). For example, the number of river restoration projects implemented annually between 1990 and 2003 increased approximately 13-fold from 400 in 1990 to 5,500 in 2003, of which 60% aimed to improve habitat for salmon and trout in the Pacific Northwest and California (Bernhardt et al., 2005; Roni et al., 2010). The popularity of river restoration has led to extensive publications which guide project design and implementation (Roni et al., 2002). Techniques for stream habitat improvement vary, but commonly include riparian planting, exclusion of livestock, removal of barriers to fish passage, erosion control, floodplain habitat improvements, and placing instream structures to create or improve fish habitat (Bernhardt et al., 2005; Carah et al., 2014; Howson et al., 2012; Roni et al., 2010, 2014). In California, the Department of Fish and Wildlife published the fourth edition of the California Salmonid Stream Habitat Restoration Manual in 2010 to guide for improving stream habitat. This manual provides a list of basic structural materials (e.g., gabions, logs, rootwads, and boulders) that are employed to construct large-wood complexes or other engineered structures to improve habitat conditions by mimicking the characteristics of natural stream structures (Carah et al., 2014; Gallagher et al., 2012).

While significant efforts in understanding river restoration projects impacts on river ecosystems have increased, monitoring programs have received substantial attention and commonly focus on the effects of restoration projects on fish abundance (Cederholm et al., 1997; Howson et al., 2012; Kail et al., 2007; Koljonen et al., 2013; Nagayama et al., 2010; Solazzi et al., 2000; Stewart et al., 2009) or geomorphic dynamics (Carah et al., 2014; Poppe et al., 2016; Tompkins et al., 2007). Other monitoring programs used a combination of indicators that integrate macroinvertebrate populations and aquatic fauna in addition to fish abundance and geomorphic aspects (Gerhard et al., 2000; O'Neal et al., 2016; Pilotto et al., 2016). Largely driven by this traditional approach and perception in ecological monitoring, the environmental impacts associated with the implementation of the river restoration projects remain unknown.

In 2009, the California Environmental Quality Act Guidelines were amended to require the analysis and mitigation of greenhouse gas emissions as part of the environmental impact assessment process. With the enactment (CEQA Guidelines 15,064.4), all lead agencies in California “must analyze the greenhouse gas emissions of proposed projects, and must reach a conclusion regarding the significance of those emissions.” (California Governor’s Office of Planning & Research, 2019) The research and applications of Life-cycle assessment (LCA) have gained increasing attention with a publication number that has grown rapidly by nearly 30 times from 1999 to 2018 (He et al., 2020). It quantifies both the direct and indirect resource use and emissions associated with a product or service, i.e., along the entire life cycle from resource extraction, manufacturing, distribution, use, to end of life management (Marsmann, 2000; Pryshlakivsky et al., 2013). It has also become a standard approach to estimating the environmental impacts, particularly on global warming, of products and services (Guinée et al., 2011; Wiedmann et al., 2008; Yang et al., 2018).

Given its accounting-oriented feature, life-cycle assessment can be used to identify hot-spots (e.g., high-impact processes) and improvement opportunities and determine more environmentally friendly alternatives (Ameli et al., 2017; Yang, 2016). Since LCA was

proposed and gradually transformed dated back to 1960s, this analytical method has been applied across a wide range of projects from construction, damming, wastewater treatment, to general civil engineering (Barandica et al., 2013; Brondani et al., 2020; Cambria et al., 2012; de Fátima Castro et al., 2015; Dias et al., 2012; González-García et al., 2013; Han et al., 2015; Suwanit et al., 2011; Zhang et al., 2015). However, in all these similar applications in estimating the environmental impact of an engineering project, these former studies involved a specific product, or a static function which can be described as a functional unit. Lately, LCA is also frequently adopted to investigate the environmental influence of events, such as conferences or exhibitions, in which physical outputs can be found to represent suitable functional units. These may include static number of booths, footprint of venues, or an entire event consisting of a specific configuration of settings (Hischier et al., 2002; Toniolo et al., 2017).

Although the completion of a restoration project can be recognized as an event, its physical properties often have weak correlations with anticipated outputs. As functional units are centered in LCA studies, the variable functions achieved by a restoration project are dynamic in nature (Kondolf et al., 2006; Palmer et al., 2005; Suding et al., 2006), making the application of LCA in restoration projects challenging. Moreover, the adaptation of LCA for quantifying impacts on ecological properties is also a documented limitation (Winter et al., 2017). Therefore, the suitability and implementation of LCA in quantifying environmental impacts of a restoration project requires further investigation. To meet these objectives, we studied the Lower Scotts Creek (LSC) Stream Floodplain and Habitat Enhancement Project in Davenport, California, to determine the feasibility of LCA to assess the impact associated with ecological river restoration, and the impact magnitude of such type of engineering projects. Total carbon footprint, or life-cycle greenhouse gases (GHG) emissions were selected as an indicator to communicate the results, and it can be mitigated under different alternative restoration designs and strategies. A novel topographic diversity index (TDI) was developed to quantitatively represent the functionality of a river restoration project, and hence, the environmental impact associated with achieving a certain level of habitat improvement. Construction documents from the LSC restoration project were compiled and analyzed to derive data of material and energy utilization throughout the project implementation. This study also aimed at providing an LCA framework tailored to ecological river restoration for future studies.

2 Materials and methods

To quantify the carbon footprint of the LSC restoration project, both field data and a third-party LCA databases were incorporated in this study as the foreground and background data sources, respectively. Field data and construction information were first compiled for the three major project implementation phases, namely, (1) raw material production, (2) raw material transportation, and (3) on-site construction. The compiled data were then connected with relevant background information from third-party data sources, EcoInvent v3.2 (Ecoinvent Centre, 2018), to calculate GHG emissions from each phase. This step was implemented in an LCA software program, OpenLCA (GreenDelta, 2018), to quantify the environmental impact per TDI (topographic diversity index) change. TDI is a novel functional unit proposed in this study, which reflects achievement of a river restoration project and enables a comparison between different project outcomes with different levels of GHG emissions. Results were also expressed in per-meter basis to give a more intuitive

understanding of GHG emission associated with the length of river habitat restored in a project. Last, key contributors were identified and the extent to which alternative engineering designs and material acquisition strategies could reduce emissions was explored.

2.1 Project background and site description

River restoration encompasses a wide range of practices, and can be broadly defined as an attempt to return river ecosystem functions to pre-disturbance conditions (Kauffman et al., 1997). Among the various engineering techniques adopted to achieve this ecological goal, placing wood structures in stream channels has been commonly applied (Roni et al., 2014). Restoration efforts that introduce large wood aim to mimic the ecosystem services and microenvironment that coarse woody debris can provide, which can increase the amount and quality of crucial over-wintering and summer low-flow habitats (Carah et al., 2014; Gallagher et al., 2012). Typically, instream structures that incorporate large wood are built using imported logs or by directly falling riparian trees into the channel. These structures can be stabilized by incorporating logs, boulders, rebar, steel cabling, epoxy, and other engineered materials. Constructing these wood features often requires the use of heavy machinery and small-engine equipment, such as log skidders, excavators, front-loaders, chainsaws, dump trucks, and other machinery to manipulate and place hefty materials (Carah et al., 2014; Kail et al., 2007). The ecological outcomes of these wood structures have been widely studied, and evidences of their effectiveness to improve habitat condition have been stated (Hilderbrand et al., 1998; Roni et al., 2002, 2010, 2014).

By recognizing the advantage of incorporating ecologically-sound engineering, the LSC project was conducted between 2014 and 2016 to enhance the ecological integrity and connectivity along the floodplain and aquatic habitat. Hydrological remedy structures were installed along the lower reaches of Scotts Creek, located on the Central Coast of California along the north Coast of Santa Cruz County (Fig. 1). The stream originates between 500 and 600 m in elevation and drains to the ocean approximately 19 km north of the city of Santa Cruz (Hillard, 2015). Scotts Creek maintains the only persistent population of Central California Coast Coho Salmon (*Oncorhynchus kisutch*) in the Santa Cruz Mountains Diversity Stratum. Coho salmon populations within Scotts Creek have been very low due to habitat degradation associated with a legacy of dredging, channelization, wood removal, clearing of riparian forest, and the construction of levees (National Marine Fisheries Service, 2012). Therefore, the goals of the LSC restoration project were to restore floodplain connectivity and improve salmonid habitat conditions by removing short sections of the levee, and by creating alcove habitat, off-channel pool connections, tributary connections, and large wood complexes.

The entire restoration project was completed in two consecutive phases targeting different channel segments (Fig. 1). Creek segments restored in C-I (2014–2015) and II (2015–2016) measure approximately 275 m (m) and 210 m, respectively. Creek segment restored in C-II is situated immediately upstream of segment restored in C-I. A topographic survey was conducted for C-I in summer 2014 (pre-project) and in summer 2015 (post-project), covering 160 m out of the 275 m of constructed reach. For C-II, the same topographic survey procedure was performed again in summer 2015 (pre-project) and in summer 2016 (post-project), covering 125 m out of the 210 m of restored reach. These two creek segments appear to have similar physical and hydrological features such as substrate size, wetted width, and depths. Results from the field survey indicate that the channel

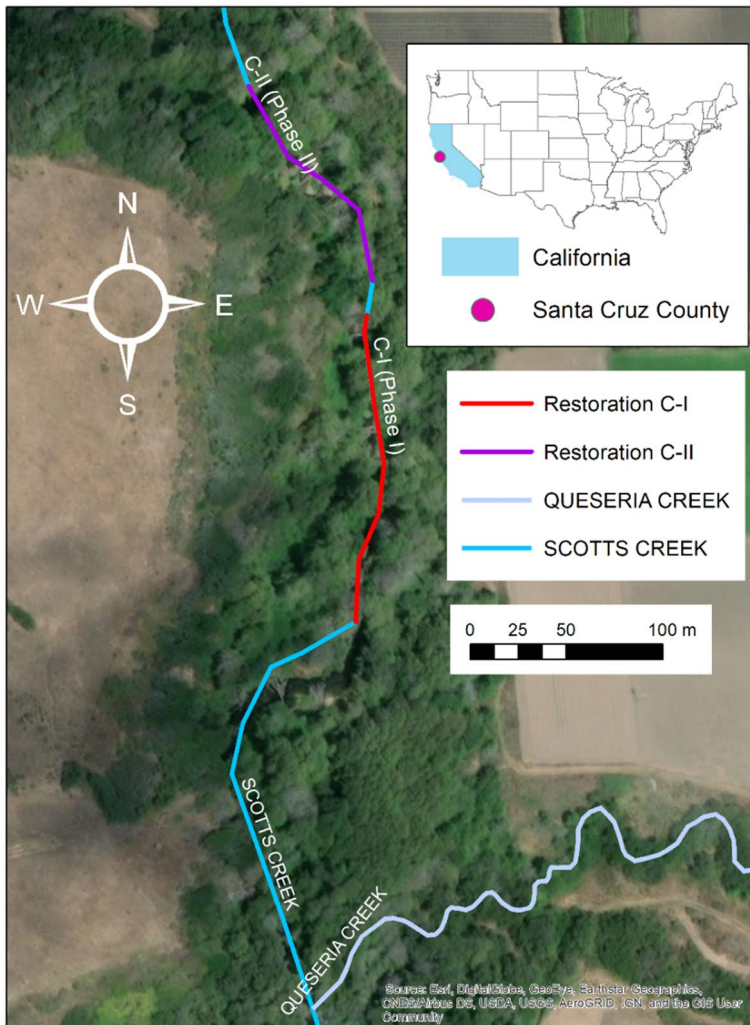


Fig. 1 Location of Scott's Creek, and the restored stream reaches

substrate is made of similar alluvial substrate with a dominant substrate of mudstone and a minor component of granitic rocks from upstream.

To incorporate ecological-engineering principles, minimal natural materials were utilized and preferred over artificial ones. Within each study reach four large wood complexes were installed, which were composed of a redwood log, boulder ballast, rootwad, and in-situ red alder (*Alnus rubra*). Industrial strength metal couplers created flexible connections between rootwads, boulders, redwood logs, and in some cases to fasten logs against brace trees (Fig. 2). This design is dubbed “franken-log” because it mimics the form of a living tree. The metal couplers create flexible connection allowing the rootwad to lift during high flows. Theoretically, this action can force water beneath the rootwad to scour into the channel bed. These large wood complexes serve a critical role to increase instream complexity, initiate channel scour, increase instream refuge habitat, and/or redirect flow

into off-channel features. In C-I, a failing levee was excavated in four locations to increase floodplain connectivity and opportunity for refuge habitat during high-flow periods. In C-II, an alcove was excavated at one location for refuge habitat (Cook, 2016). The design of the project is similar in both phases, the major difference being the amount of material excavated in off-channel features (Table 1).

2.2 A novel functional unit: topographic diversity index (TDI)

A primary goal of river restoration is to improve habitat biodiversity, as higher biodiversity correlates with enhanced ecosystem service (Benayas et al., 2009). Therefore, to be in line with the nature of river restoration projects, we established TDI as the functional unit of carbon footprint analysis in this study. The index reflects improvement in the functioning and services associated with a restored river habitat, and thus can be employed to evaluate a project outcome and to compare the significance between alternative designs.

With the initial intention to assess the effectiveness of implanting large wood structures, topographic surveys were conducted for pre- and post-project conditions in both C-I and C-II reaches. These topographic surveys used a total station (optical surveying equipment) to assess changes in the physical habitat that may have resulted from project installations, particularly from large wood complexes. In this study, the collected topographic data were further adopted to calculate TDI, which quantified the channel complexity before and after the restoration. TDI was then adapted to assess major changes in habitat types and to develop an approach that integrates LCA results for quantifying the environmental performance of a restoration project.

To calculate TDI, a total station was used to collect topographic survey data for C-I in summer 2014 (pre-project) and spring 2015 (post-project) and, similarly, for C-II in summer 2015 (pre-project) and summer 2016 (post-project). These surveys generated four digital elevation model (DEM) maps that captured the topography of the active channel, nearby streambanks, and adjacent floodplain surfaces. Grid values from these maps were then converted to depict in-stream topographic diversity by adapting the concept of Shannon's Diversity Index. Conceptually, each elevation class corresponds to a cohort of species in a community and the area size of each elevation class represents the population size of a species. To convey this concept, each DEM raster map layer was reclassified into one-foot (or 30.48 cm) elevation categories, of which area size can be computed and statistically summarized by geospatial tool such as ArcMap®. The TDI is calculated by transforming Shannon's Diversity Index (Krebs, 1972) as:



Fig. 2 Images of the woody structures positioned in the construction sites to regulate flow direction

Table 1 Summary of stream characteristic for C-I and C-II in Lower Scotts Creek, and corresponding materials utilized for construction

Measurement	Unit	C-I	C-II
Construction period		2014–2015	2015–2016
Restored reach length	m	275	210
Topographic survey coverage	m	160	125
Average wetted width	m	6.15	7.15
Average water depth	m	0.35	0.42
On-site Construction Machinery and Operational Time	Unit	C-I	C-II
<i>Construction material</i>			
Boulder ballast	kg	14,516	18,144
Redwood log	m ³	7.83	7.83
Metal coupler	kg	8	8
Wheat straw as a mean of mulch	kg	490	245
<i>Construction machinery</i>			
Log skidder operation	hr	1.1	1.3
Utility tractor operation	hr	20	19
Hedge trimmer operation	hr	12	14
Chainsaw operation	hr	20	16
Power pole pruner operation	hr	5.5	6.25
Backhoe loader operation	hr	16	8
Track loader operation	hr	10	0
Excavator operation	hr	66	50
Portable power generator	hr	8	9
<i>Transportation</i>			
Flatbed truck operation as passenger vehicle	p × km	258	453
Flatbed truck operation as transportation vehicle	kg × km	40,044	22,520
Combination trucks	kg × km	5,588,123	7,869,691
Light commercial truck (diesel)	kg × km	174,179	188,694
Dump truck operation	kg × km	423,836	243,851

$$TDI = - \sum_{i=1}^R (A_i/A_T) \ln (A_i/A_T)$$

where A_i equals the area in an elevation class i , A_T is the total area size of a study site, and R equals the total number of elevation classes. In the original form of Shannon’s Diversity Index, A_i and A_T are displaced by population of each species and the total population size within a studied area, respectively.

Carbon footprint analysis was then conducted on the basis of 1% change in TDI from the baseline condition (pre-project status). Results were also expressed in terms of per meter of river restored to give a more intuitive understanding of GHG emissions associated with ecological river restoration.

2.3 Carbon footprint analysis

Three major life cycle phases were included in our analysis: raw material production, raw material transportation, and on-site construction (Fig. 3). In the raw material production phase, GHG emissions occurred during the collection and production of the raw materials, including logs, boulders, and metal pieces used to conduct the restoration project. Specifically, emissions from producing metal couplers, quarrying boulder ballasts, harvesting red-wood logs, growing straw mulch for erosion control, excavating rootwads, and harvesting plant materials were estimated. Machinery operation time and the dimensions and specification of all engineering materials utilized on site were documented in the construction reports and field notes administrated by the management of Swanton Pacific Ranch where the river restoration project took place. All the large equipment, including excavators, tractors, and skidders, were rented from different vendors located between 12 and 104 km away from the construction sites. The fuel consumption and associated emissions resulting from transporting the heavy machinery were estimated in this study.

The on-site construction phase consisted of five major activities: site preparation, installing off-channel features, installing wood features, conducting erosion control, and revegetating disturbed areas. Erosion control and revegetation primarily used hand tools and small trucks to move staff and materials around the site. Site preparation primarily used small-engine equipment to create access corridors for heavy equipment along riparian areas. Installing off-channel features and wood features required the use of a variety of heavy equipment including excavators, skid steers, and dump trucks. Emissions came primarily from equipment use, which was a focus of our analysis as it has been a frequently documented hotspot in previous studies that involved preparation or modification on forested sites (Cambria et al., 2012; Dias et al., 2012; González-García et al., 2012; Han et al., 2015). Emission data were obtained from Ecoinvent v3.2 (Ecoinvent, 2015) and the U.S. Life Cycle Inventory Database published by the National Renewable Energy Laboratory (National Renewable Energy Laboratory, 2012). GHG is then measured in CO₂ equivalent (CO₂e) by multiplying each greenhouse gas’ global warming potential published in Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) (Bare, 2002). Note that emissions associated with developing capital assets, building machinery, and performing office administrative

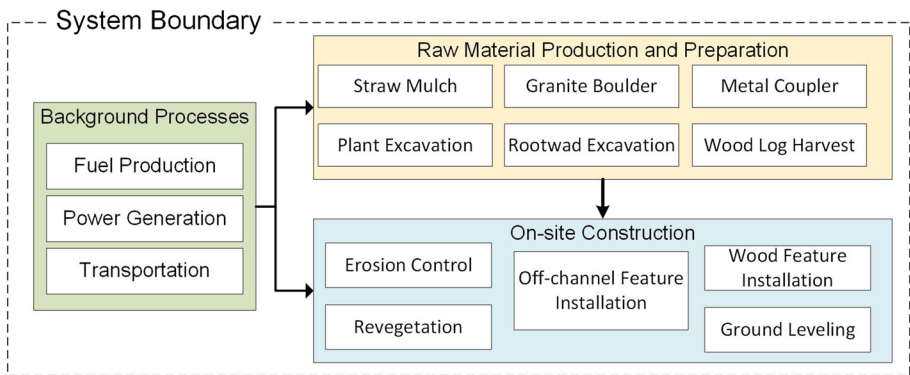


Fig. 3 Schematic diagram for the stream habitat improvement processes with the cradle-to-gate system boundary

tasks were excluded from the studied system. Finally, all datasets were input into an open-source LCA software program OpenLCA (GreenDelta, 2018) for processing, analysis, and life-cycle computation.

2.4 Impact mitigation via alternative designs and strategies

Four emission reduction scenarios were explored. The first scenario employed accelerated recruitment technique, the second adopted an alternative plant sourcing technique, the third reduced machinery delivery distance, and the last one integrated all aforementioned planning strategies (Table 2). In the in-situ alder scenario (IAS), an accelerated recruitment method was incorporated in the wood material acquisition scheme. The accelerated recruitment technique involved falling red alders (*Alnus rubra*), which may be growing on the streambank or floodplain. Once these trees fall, they are placed unanchored into the stream to manipulate flow (Carah et al., 2014). This scenario represents a project plan configuration that relies only in-situ round wood found at or near construction sites, but would increase the excavator operating time required to install wood features by 15% due to falling and positioning in-situ red alders. In the plant sourcing scenario (PS), plants were sourced from a nearby plant nursery (greenhouse) rather than utilizing in-situ plants found near the construction site. All plants used to conduct revegetation in the baseline case would be grown in the nursery. Plant composition was assumed to be 20% trees (weighing 4.5 kg each), 30% mid-sized plants (weighing 2.3 kg each), and 50% smaller shrubs (weighing 0.45 kg each). In the scenario of Machinery Delivery Distance Reduction (DS), machinery was rented from nearby sites that were 50% closer than in the baseline case.

3 Results and discussion

3.1 Quantifiable functional unit as percent change of topographic diversity

The percent TDI (topographic diversity index) change ($\Delta\text{TDI}\%$) is nearly identical in each reach, approximately 8% in C-I and 9% in C-II, with an average TDI of 1.8 (Table 3). Figure 4 shows the distribution of elevation gradient in C-I and C-II reaches, with the

Table 2 Summary of the schematic configuration of each scenario tested in this study

Scenario	Sourcing Large Wood Complex	Changing Wood Feature Installation Time (%)	Sourcing Seedling for Revegetation	Changing Distance to Obtain Rental Machines
Baseline (Bas)	External sources	100	In-situ plants	0
In-situ Alder acquisition (IAS)	In-situ	115	In-situ plants	0
Plant sourcing (PS)	External sources	100	Local nursery	0
Machinery delivery (DS)	External sources	100	In-situ plants	50%
Integrated scheme (Intg)	In-situ	115	Local nursery	50%

Table 3 Area (m²) and TDI value for each elevation category in C-I and II

Segment Elevation(m)	C-I		C-II	
	Pre	Post	Pre	Post
2.3–2.4		0.33		
2.4–2.7	1.52	3.91		0.51
2.7–3.0	19.70	28.41	0.01	2.08
3.0–3.4	50.39	44.20	1.25	4.21
3.4–3.7	92.39	67.43	8.84	11.89
3.7–4.0	35.72	45.90	37.27	49.74
4.0–4.3	19.64	30.68	73.39	52.81
4.3–4.6	14.08	13.66	40.02	41.03
4.6–4.9	8.03	8.14	23.97	24.08
4.9–5.2	2.34	2.15	14.91	12.05
5.2–5.5			6.78	7.71
5.5–5.8			1.57	1.77
5.8–6.1			0.05	0.16
TDI	1.73	1.88	1.75	1.90
TDI change (Δ TDI%)		8%		9%

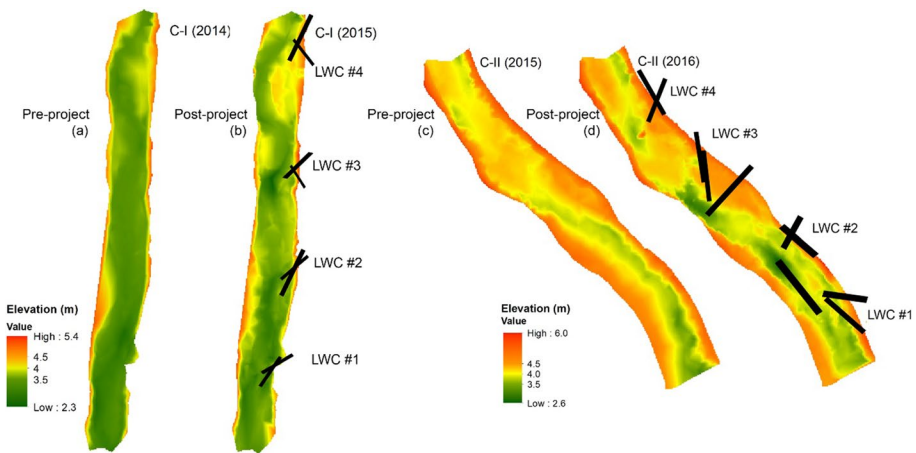


Fig. 4 Distribution of DEM change of studied channels C-I (a, b) and C-II (c, d), between pre-project (a and c) and post-project (b and d) conditions

positions of large wood complex in both restored segments. With only a year of transformation induced by the in-stream features, the increase in TDI indicates positive response in habitat enhancement. Within a year of morphological transformation, C-I experienced one bankful flood event, whereas C-II experienced multiple incidents. Given the short interval, the hydrological regimes occurred during the measurement does not have significant impact on changing TDI.

TDI results also indicate spatial transformation between the presence of large wood complex and deep pool formation in both C-I and II (Fig. 4). Large wood complex No. 3 (LWC #3 in Fig. 4b) in C-I generated a deep pool (residual pool depth of 95 cm

approximately) near the tip of the structure. LWC #2 and #3 in C-II generated deep pools at the downstream end of the logs, with residual pool depths ranging from 98 to 131 cm (Fig. 4d). Aside from forming deeper pool habitats these structures tended to break up stream flow. When the stream flow was disrupted a slow-water area often formed downstream and behind large wood complexes. These slow-water areas generally led to an accumulation of material in the slow-water area. These depositional features were noted on the left bank behind LWC #4 in C-I and on the left bank behind LWC # 4 in C-II. The subsequent deposition and erosion led to an increase in TDI in both C-I and II.

3.2 GHG emission and key contributors

The GHG emission of restoring a river habitat in our study averaged 10.9 kg CO₂e per meter (8.7 kg CO₂e for C-I and 13.7 kg CO₂e for C-II), and 312.7 kg CO₂e per 1% increase in TDI (288.5 for C-I and 336.2 kg CO₂e for C-II). The total GHG emissions caused by ecological river restoration per project averaged 2.6 Mg CO₂e, ranging from 2.4 to 2.9 Mg CO₂e (Table 4).

Notwithstanding many consistencies between the environmental profile of C-I and II, there were several factors contributing to the higher GHG emission from C-II than C-I as many start-up requirements were the same despite the fact that a shorter creek reach was restored in C-II. For instance, C-II resulted in 1.8 times higher GHG emission in the wood feature installation phase alone on a per-project basis, primarily due to the longer transportation distance for acquiring rootwad (compared 68 to 30 km) and boulder ballasts (compared 182 to 64 km). This difference is amplified on a per-meter basis leading to 2.4 times higher GHG emission for C-II than C-I. In addition, both projects required renting heavy equipment from adjacent vendors resulting in 1.1 and 1.0 Mg CO₂e of GHG emission per project from C-I and II, respectively, translating to 3.9 and 4.7 kg CO₂e/m of GHG. Therefore, C-I appeared to have a better configuration and schematic design than C-II leading to a GHG reduction ranging from 18 to 58% compared to C-II on a per-meter basis throughout wood feature installation, heavy machine transportation, and site preparation. However, the significance in marginal GHG reduction of C-I to C-II is decreased on a basis of per-TDI% change, a 16% reduction compared to 36% on the per-meter basis.

Table 4 GHG emissions (kgCO₂e) associated with each phase in the two restoration projects (C-I and C-II) under different functional units

Project Phases	C-I	C-II	Length-weighted Average	TDI-weighted Average
Installing wood features	884	1614	1200	1255
Transport heavy equipment	1061	992	1031	1026
Installing off-channel features	335	139	250	235
Site preparation	61	110	83	86
Revegetation activities	37	18	29	28
Erosion control	26	13	20	19
Project Total Emission	2404	2887	2613	2649
Emission Per meter (kgCO ₂ e/m)	9	14	11	–
Emission Per TDI% Change (kgCO ₂ e/ΔTDI%)	288	336	–	313

Contribution analysis indicated a similar pattern for both project sites (Fig. 5). The majority of impacts came from transporting heavy machines or installing wood features in LSC projects, which represented the greatest time- and fuel-consuming activities in river restoration and required the largest material inputs. On a per-meter basis, installing wood features was responsible for 3.22 kg CO₂e (37%) of the total GHG emissions in C-I, and accounted for 7.69 kg CO₂e (56%) of the total GHG emissions in C-II (Fig. 6). The largest amount of GHG emissions were from transporting redwood logs from their origins to the restoration sites accounting for 21% and 43% of GHG emission in C-I and C-II, respectively.

The operation of fuel-powered equipment such as excavators and large-haul trucks were other key impact contributors. Overall, this category of activities resulted in 20% and 12% of the total emissions in C-I and C-II, respectively, amounting to 1.76 and 1.68 kg CO₂e/m, or 33.82 and 24.42 kg CO₂e/ΔTDI%. The remaining GHG emissions were contributed by the man-made material acquisition, including adopting boulder ballast, metal coupler, and wheat straw as an erosion-control means. The employment of man-made materials accounted for approximately 9% of total GHG emissions in both restoration projects. Our result reinforced previous findings that the operation of heavy equipment can be a substantial source of GHG emissions in systems involving forest operation (Dias et al., 2012; S González-García et al., 2014; González-García et al., 2014; Sara González-García et al., 2014; González-García et al., 2014; Han et al., 2015).

Figure 6 can also illustrate the effect of functional units in changing the result, which indicates the suitability of TDI as a functional unit representing dynamic services that can change over time. The marginal change between C-I and C-II is substantially smaller ranging from 20 to 30% in the per-ΔTDI% results than those in a per-meter basis (58–75%). Because ecological objectives are achieved by the strategic configuration of engineering properties in a project, rather than the size of constructed areas, LCA results represented

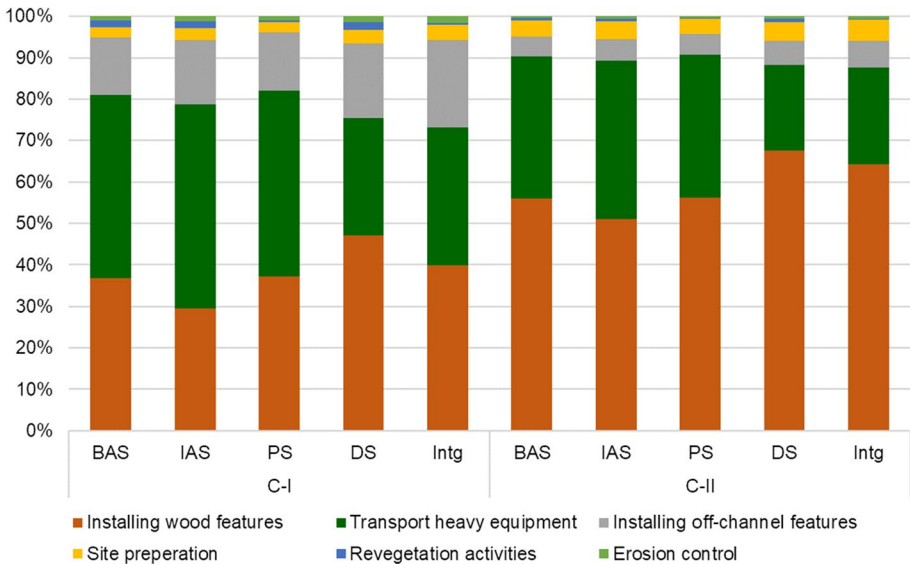


Fig. 5 Impact contributor in C-I and II under different scenarios. (BAS—Baseline scenario, IAS—Alder acquisition, PS—Plant sourcing, DS—Machinery delivery distance reduction, Intg—An integrated scenario of all three of AS, PS, and DS. See Table 2 for detailed definitions)

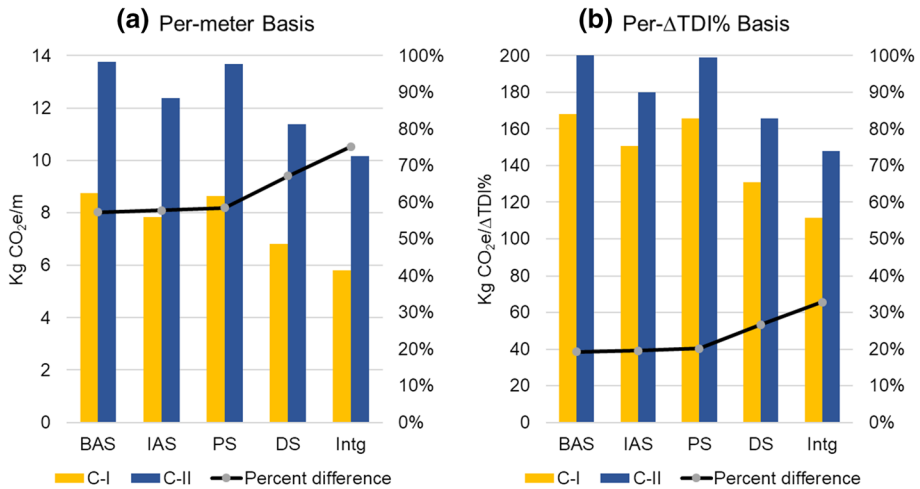


Fig. 6 Per-meter and per- Δ TDI% impact of C-I and II under different scenarios. Black lines indicate the percent change of C-II from C-I based on different functional units

in a TDI basis can provide better insights in reflecting the environmental implications of a dynamic product system such as restoration projects.

The performed function and ecological services provided by such engineering projects as river restoration can be dynamic and changed over time. Enhancing habitat quality as an unconventional deliverable of a product system can increase the challenge to adopt LCA by following former published experience. In this study, results were presented on both physical (meters of river restored) and ecological (topography diversity) bases, which can articulate the effects of selecting functional units to improve the interpretation of LCA results. The performance of river restoration projects often time has little to do with the physical and engineering inputs which are highly correlated to environmental impacts. The LSC restoration effort particularly revealed the lack of correlation between the physical properties of a construction site and its ecological outcomes. By changing the quantitative reference from per-meter to per-TDI change basis, the marginal difference in carbon footprint between C-I and C-II is decreased (Fig. 6). The result indicates that using an ecological functional unit than a physical unit can enhance the ecological relevancy to quantify the environmental impact of restoration projects.

3.3 Emission mitigation potentials

Across mitigation scenarios, renting heavy machines from closer sites would be most effective in reducing GHG emissions, with a reduction potential of 22–17% of GHG in C-I and C-II, respectively (the DS scenario; Fig. 6). On the other hand, sourcing plants from a nearby nursery was the least effective, with GHG reduction as little as 1% (the PS scenario). Adopting an accelerated alder acquisition technique would lead to a moderate degree of emission reduction (the IAS scenario). The configuration would mostly affect the phase of large wood complex installation by reducing the transportation intensity associated with delivering redwood logs from their origins to the restoration sites. However, this attempt required longer on-site machine operation time to properly position alders, thus, offset the benefit of reducing GHG emission from shortening transportation. Moreover, the

cultivation of redwood contributed little (0.6%) to the total GHG emission throughout a project's life cycle. Project crew's experience and proficiency in on-site machine operation can directly contribute to the effectiveness of GHG reduction by minimizing fuel consumption. If all measures were taken, the total GHG reduction potential can be as high as 26–34% (Fig. 6).

Although processes required to install wood features were key contributors to emissions in this river restoration project, they were also central to the design of the LSC. Instream large wood is known to benefit salmonid habitat (Howson et al., 2012) particularly for the formation of deep pools (Roni et al., 2014). The effectiveness monitoring data suggested a positive response from the accelerated recruitment method, particularly in C-II. LWC # 3 in C-II initiated thawleg (a line connecting the lowest point of the stream) migration which caused a large multi-stemmed red alder to fall (Fig. 3d). This semi-natural recruit also contributed to the change in pool-riffle sequences and dynamics. The alder spanned more than two times the channel width and had a diameter at breast height (DBH) of > 70 cm on its largest stem. Multiple studies suggest that logs greater than 1.5 times the channel width were retained at higher rates than shorter logs (Carah et al., 2014). Another study found that logs greater than 60 cm in diameter tended to form a higher proportion of pools than did thinner logs (Rosenfeld et al., 2003). However, the increase in log sizes can also attribute to elevated GHG emissions. For instance, increasing log diameter by 10% can lead to the increase of GHG by 21% for logging process alone. Throughout the LSC life cycle, the increase of wood log volume by 10% can contribute to additional 1.13% or 1.07% of GHG in C-I and C-II projects, respectively. One way to circumvent and offset the elevated emissions resulted to acquiring large-size logs is to use the accelerated recruitment method, which cuts or excavates trees growing on or nearby the streambank and places them into the channel to modify flow regimes and increase habitat complexity. A former study demonstrated the promise of this method, finding that recruited trees reliably improved habitat, retained wood over the short term, and had the potential to increase the scale and efficiency of the river restoration process (Carah et al., 2014). Results derived from the in-situ alder scenario (IAS) indicated that this strategy can reduce overall emissions by 10% in both restoration sites by introducing alders found on-site. This approach can omit the use of external wood materials, hence lower transportation requirement. This study provides justification to incorporate the accelerated recruitment method to not only achieve the environmental goal of GHG reduction, but also advance ecological goals. Therefore, by taking into consideration the environmental benefit of reducing GHG emissions, as shown under the alder scenarios (IAS), the introduction of in-situ roundwood material can be considered as a feasible technique to meet both ecological and environmental goals.

On the other hand, results from this study revealed that strategically acquiring seedlings from different sources did little to reduce GHG emissions. The total emissions under the plant sourcing (PS) scenario were lower by 1% than under the baseline scenario in both C-I and C-II projects. As many restoration projects discussed the variation of sourcing seedling strategies for achieving ecological goals (Guillozet et al., 2014; Mills et al., 2007), seedling sourcing strategy is more of an ecological means than environmental measurement. In the baseline scenario, a mid-sized backhoe was used to excavate various species of rush which were later gathered for revegetation purposes. Acquiring native plants from project adjacent areas also preserves genetic stock. However, from a life-cycle perspective, using nursery grown plants and transporting the plants a short distance proved to be less impactful, compared to the baseline case. Although using nursery seedling would lead to additional emissions from greenhouses management and transportation, it would also omit the operation of the backhoe which was the dominating impact contributor in the baseline

revegetation process. Moreover, the PS scenario considered a representative nursery close to LSC, with low emissions associated with hauling seedlings from the nursery to the job site. Actual emissions could be higher with greater distances to a nursery. Therefore, to balance ecological and environmental goals, project managers should consider sourcing seedlings from locations where they require minimal transportation inputs or field operation for in-situ seed or plant collection. However, it is worth noting that the scenario analysis conducted in this study did not gauge ecological progress under different engineering settings. Thus, we assumed different project configurations would all lead to the same TDI change. This might not be a sustainable assumption, especially under the PS (plant sourcing) scenario.

The machinery delivery scenario (DS) indicated that haul distance was a major contributor to the total GHG emissions. Reducing the haul distance for renting heavy machines used in accomplishing restoration projects of C-I and C-II would reduce emissions by 22% and 17%, respectively. This scenario was conducted because renting heavy machine and field equipment in a restoration project is an important decision from the aspect of project planning and management. An important question leading to this assessment was, to what extent would using equipment rentals closer to the site reduce GHG emissions? Some river restoration projects take place along very remote sections of river which are difficult to access. From a life-cycle prospective, these results indicate that strategic business decisions can also lead to significant environmental improvement.

3.4 Result proxy and future studies

This study was the first to apply LCA to the river restoration process. Therefore, it is difficult to compare it with others. Several studies with similar proxies as the LSC project were reviewed to derive approximate insights and to put results from this study into perspective. One study examined the impacts of several management scenarios in redwood forests, and the authors documented that approximately 49% of GHG emissions across various scenarios were associated with primary transportation (Han et al., 2015). Primary transportation involved yarding logs from the stump to the landing and was the most time-consuming part of the timber harvesting processes in their studied system. If roughly half the impacts from the manual-ground based system in an un-even aged management scenario were from primary transportation, GHG emissions would be ~ 12.4 Mg CO₂e per entry or a harvested timber stand. In comparison to LSC baseline scenarios, river restoration emitted ~ 5.3 Mg CO₂e to restore a total of 485 m of stream. Both primary transportation and river restoration use heavy machinery to transport and manipulate logs over rough terrain. There are certain interplays between the river restoration and timber harvest. For instance, primary transportation in a forest system may involve the operation of several log-skidders, an excavator, or a front-end loader, similar to what can be used in conducting river restoration. However, significant variations between these two types of activities need to be noted. For example, logging operations tend to be large-scale and may take longer to complete, compared to the LSC restoration that took approximately three weeks for C-I and two weeks for C-II.

Other studies documented the impacts associated with site preparation of timber production that resulted to approximately 3 kg to 5.6 kg CO₂e per m³ of roundwood logging (Dias et al., 2012; Sara González-García et al., 2014; González-García et al., 2014). The logging stage referred to final cutting, forwarding, and loading onto trucks, which is similar to the site preparation in LSC restoration. To put this into perspective, the site preparation

in LSC restoration projects led to an average of 10.9 kg CO₂e per meter stream restored, or 182 kg CO₂e per TDI percent change. As timber harvest and river restoration show distinctly different goals, the magnitude of work involved in site preparation for each type of project are significantly different, despite that both may incorporate similar equipment to achieve similar objectives. Therefore, it is expected that site preparation for timber harvest can be much higher on a per-meter project basis, whereas the results on a basis of per-TDI percent change are incomparable as the functional unit are drastically different.

4 Conclusions

To our best knowledge, it has not been a common practice to address environmental life-cycle impact of a restoration project. By introducing LCA to a project's planning phase, project managers can address their performance from a broader perspective than relying on existing matrices that solely focus on improving habitat quality. This study bridges the disciplines of ecological engineering and life-cycle analysis to present the functionality of river restoration and to estimate the magnitude of environmental impact associated with it. The result suggests that river restoration projects should take additional environmental costs into consideration while aiming for ecological goals. Although the so-called ecological engineering approach adopted by recent river restoration planning has gained significant attention, our study demonstrates that river restoration projects can also meet environmental goals by strategically renting heavy machines from a near vendor, and to acquire in-situ natural materials as means for achieving both ecological and environmental objectives. In this study, we proposed the change of TDI as a novel way to quantify the environmental performance of river restoration. TDI adapted topographic survey data to quantify the complexity of a stream channel and provide a functional unit for the LCA study. This study also contributed to the establishment of an environmental impact assessment framework. With the increase in field data compiled from future restoration sites, management agencies can incorporate this assessment framework to elaborate the environmental implications associated with ecologically dynamic projects. In the future, systematic assessment can be conducted to compile site-specific data by deploying the same LCA framework as this study. Such studies can enhance the comparability among different projects by increasing data availability and restoration performance based on the change of TDI. The consistency in methodology and choice of functional units will provide detailed insights on how site configuration can affect the environmental portfolios of restoration project at a landscape level. The increase in accumulated data and information can also support the development or enhancement of relevant regulations (such as CEQA) by providing a common baseline to put the environmental portfolio of restoration projects into perspectives.

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