Conservation Biology

Review

Compliance with and ecosystem function of biodiversity offsets in North American and European freshwaters

Sebastian Theis,[1] Jonathan L.W. Ruppert,[1,2]* Karling N. Roberts,[1] Charles K. Minns,[3] Marten Koops,[4] and Mark S. Poesch[1]

[1]Department of Renewable Resources, University of Alberta, 751 General Services Building, Edmonton, Alberta, T6G 2R3, Canada
[2]Toronto and Region Conservation Authority, Research and Knowledge Management, Watershed Strategies, 101 Exchange Avenue, Vaughan, Ontario, L4K 5R6, Canada
[3]Department of Ecology and Evolutionary Biology, University of Toronto, 25 Harbord Street, Toronto, Ontario, M5S 3G5, Canada
[4]Great Lakes Laboratory for Fisheries and Aquatic Sciences (GLLFAS), Fisheries and Oceans Canada (DFO), Burlington, Ontario, L7S 1A1, Canada

Abstract: Land-use change via human development is a major driver of biodiversity loss. To reduce these impacts, billions of dollars are spent on biodiversity offsets. However, studies evaluating offset project effectiveness that examine components such as the overall compliance and function of projects remain rare. We reviewed 577 offsetting projects in freshwater ecosystems that included the metrics project size, type of aquatic system (e.g., wetland and creek), offsetting measure (e.g., enhancement, restoration, and creation), and an assessment of the projects' compliance and functional success. Project information was obtained from scientific and government databases and gray literature. Despite considerable investment in offsetting projects, crucial problems persisted. Although compliance and function were related to each other, a high level of compliance did not guarantee a high degree of function. However, large projects relative to area had better function than small projects. Function improved when projects targeted productivity or specific ecosystem features and when multiple complementary management targets were in place. Restorative measures were more likely to achieve targets than creating entirely new ecosystems. Altogether the relationships we found highlight specific ecological processes that may help improve offsetting outcomes.

Keywords: compensation, conservation, development, evaluation, lake, management, mitigation, river, stream, wetland

Cumplimiento y Función Ambiental de las Compensaciones por Biodiversidad en las Aguas Dulces de América del Norte y Europa

Resumen: El cambio del uso de suelo causado por el desarrollo humano es un causante fundamental de la pérdida de biodiversidad. Para reducir estos impactos se gastan miles de millones de dólares en las compensaciones por biodiversidad. Sin embargo, todavía son raros los estudios de evaluación de la efectividad de los proyectos de compensación que examinen componentes como el cumplimiento general y la función de los proyectos. Revisamos 577 proyectos de compensación en ecosistemas de agua dulce que incluyeran las medidas del tamaño del proyecto, el tipo de ecosistema acuático (p. ej.: arroyo, humedal), la medida de compensación (p. ej.: mejoramiento, restauración, creación) y una evaluación del cumplimiento y el éxito funcional del proyecto. La información sobre los proyectos se obtuvo de bases de datos científicas y del gobierno y de la literatura gris. A pesar de la inversión considerable que existe para los proyectos de compensación persistieron problemas cruciales. Aunque el cumplimiento y la función estuvieron relacionados entre sí, un nivel alto de cumplimiento no garantizó un

*email jonathan.ruppert@trca.on.ca
Article impact statement: *Despite legislation in places like the United States, EU, Australia, and Canada, biodiversity offsets do not show high levels of ecosystem function.*
Paper submitted September 13, 2018; revised manuscript accepted February 15, 2019.

Conservation Biology, Volume 34, No. 1, 41–53

DOI: 10.1111/cobi.13343

nivel alto de función. Sin embargo, los proyectos grandes en relación con el área tuvieron una mejor función que los proyectos pequeños. La función incrementó cuando los proyectos se enfocaban en la productividad o en características específicas del ecosistema y cuando los objetivos complementarios de manejo estaban en orden. Las medidas de restauración tuvieron mayor probabilidad de lograr los objetivos que la creación de un ecosistema totalmente nuevo. En general, las relaciones que encontramos resaltan los procesos ecológicos que podrían ayudar a mejorar los resultados de la compensación.

Palabras Clave: arroyo, compensación, conservación, desarrollo, evaluación, humedal, lago, manejo, mitigación, río

Introduction

The worldwide loss of habitat, especially over the last century, has led to a steady decline in biodiversity (Sala et al. 2000; McCauley et al. 2015). One of the major drivers of habitat loss and biodiversity declines is land-use change related to urbanization or resource extraction (e.g., Sala et al. 2000; Vörösmarty et al. 2010). When impacts to biodiversity or an ecosystem cannot be avoided or mitigated, environmental offsets can be used to preserve ecosystem function and services. The offsetting principle is founded in the no net loss (NNL) framework, which aims to counterbalance biodiversity and ecosystem service loss linked to economic development (Maron et al. 2018). Offsetting is the last step in the mitigation hierarchy, such that it is used only after avoidance, minimization of harmful impacts, or rehabilitation of the affected ecosystem following exposure have been ruled out or deemed impossible to achieve (McKenney & Kiesecker 2010) (Fig. 1).

Freshwater ecosystems are sensitive to broad spatiotemporal scale developments (Sala et al. 2000; Dextrase & Mandrak 2006; Dudgeon et al. 2006; Vörösmarty et al. 2010). Freshwater fishes have the highest extinction rate among vertebrates in the 20th century (Burkhead 2012). Besides overexploitation, habitat loss and alteration represent major threats to aquatic species (e.g., Dextrase & Mandrak 2006; Dudgeon et al. 2006). Habitat loss can occur through destruction or degradation of land cover and biological features or alteration of physical properties, such as flow regime or pollution (Dudgeon et al. 2006). Offsetting can provide one solution to these threats and is a common conservation tool for aquatic ecosystems. Most commonly it addresses 1 of 4 major project targets: species productivity, basic ecosystem function, habitat quality, or preservation (banking); Methods include creation, restoration, or enhancement of habitat (e.g., Reiss et al. 2009; Cahill et al. 2015).

Offsetting is not a new concept; it has been used for decades in some regions (e.g., United States since about 1972), but in many parts of the world it remains a novel and often experimental approach with high uncertainties regarding its effectiveness and feasibility (Moilanen et al. 2009; Curran et al. 2014). Generally, offsetting is implemented in mandated frameworks, such as the Water Framework and Habitats Directives (European Union), Canada's Fisheries Act, Wetland Mitigation and Banking Policy (United States), Australian Offset Policies, and Brazilian Industrial and Forest Offsets, and linked to regulatory requirements imposed on proponents where development affects ecosystems (Goodchild 2004; McKenney & Kiesecker 2010). In the absence of a global policy, each country has its own approach to conserving habitat and biodiversity; several offsetting approaches exist in different parts of the world (e.g., Ambrose 2000; Bull et al. 2013; Maron et al. 2015). However, evaluations of projects and regular monitoring programs beyond mandatory requirements are rarely conducted, making it difficult to evaluate actual offsetting success (Horak & Olson 1980; Roni et al. 2008; Gonçalves et al. 2015). Offsetting projects also rely on the proponents' compliance with required measures. Previous work shows that proponent compliance in offsetting projects is generally poor and monitoring data can often be superficial and seldom span an adequate time to conduct scientifically rigorous quantitative assessments (Harper & Quigley 2005*a*, 2006*b*; Quigley & Harper 2006*a*, 2006*b*; Tischew et al. 2008). Additionally, long-term success rates and efficacy of aquatic offsetting projects remain largely unevaluated or are misjudged, which makes it difficult to further develop and adapt the planning process for future or ongoing projects (e.g., Zedler & Callaway 1999; Tischew et al. 2008).

Given the importance and popularity of offsetting coupled with high uncertainty about offsetting projects, we conducted a global synthesis to determine whether particular aspects of aquatic offsetting projects are related to project compliance and ecosystem function. Specifically, we aimed to determine whether there is a relationship between compliance and function for offsetting projects and assess whether there were trends across regions, scale of the project, project targets, methods used for offsetting, and ecosystems types in terms of compliance with permits and assessed ecosystem function. Evaluating the compliance and function relationship will help determine whether high compliance in projects consequently leads to good ecosystems function or vice versa and how permits might need to be adapted in the future. Identifying potential trends can highlight

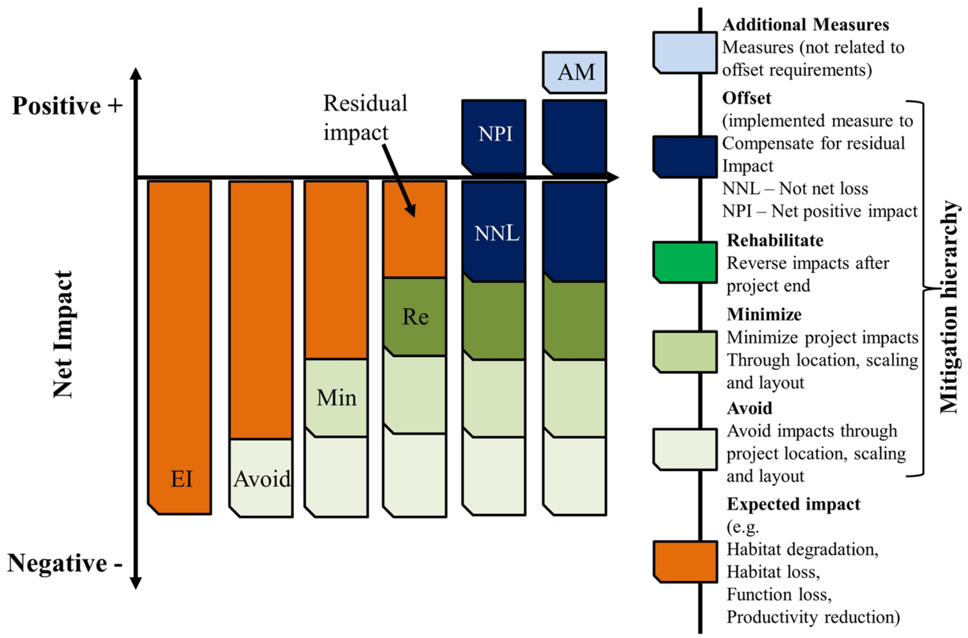

Figure 1. Offsetting principles and their place in the mitigation hierarchy in reducing residual impacts of anthropogenic influence and achieving not net loss of biodiversity and habitat area or net positive impact of an offsetting project (adapted from Kiesecker et al. 2011). EI, expected impact; min, minimize impact; re, reverse impact; AM, additional measures.

deviations between permit-related (policy) and ecosystem function–related (condition-based) assessments (Kozich & Halvorsen 2012).

Methods

Projects included in this synthesis were collected through a literature search of peer-reviewed and gray literature. The search was done using the PICO (population, intervention, control, and outcome) principle (Davies 2011). Categories were offsetting projects in aquatic freshwater systems (populations), offsetting through creation, enhancement, or restoration (intervention), presence of clearly stated goals or requirements for the respective project (control), and monitoring or evaluation of project success in regards to official permit or stated goals (outcome).

We used set of defined screening criteria to screen projects. Details of the synthesis protocol are in Supporting Information. It covers all major steps used to collect literature and synthesize relevant data (e.g., Boolean operators and accessed databases). Projects included in the study had to be associated with freshwater. Marine projects were not considered due to high uncertainties and difficulties in evaluating their success (Powers et al. 2003; Bayraktarov et al. 2016). Furthermore, projects had to include a clearly defined target and evaluation process, such as checking stated targets though validated assessment methods, from which overall offsetting success could be determined. Projects also needed to have offsetting as the main project goal by replacing, enhancing, or restoring impaired ecosystems or ecosystem aspects. Project effectiveness and success had to be determined by meeting regulatory and legally binding requirements (compliance) or ecosystem function (function) targets relative to reference systems, preconstruction assessments, or both. We found 51 usable records, which produced 637 single offsetting projects (appraisal methods in Supporting Information). Some records produced more individual project files than others (Supporting Information). Projects were distributed across 27 countries and 5 continents (Supporting Information), although most (98.4%) were in the United States (65.1%), Canada (13.5%), and Europe (19.8%) (Supporting Information).

Evaluation of Project Compliance and Function

After compiling project characteristics such as location, project size, project targets, and implementation methods, we excluded projects outside the 3 main geographic areas (low sample size, $n = 10$). We then investigated compliance and function metrics for each individual study. For compliance, this was generally based on legally binding permit requirements. Most compliance criteria fell into one of the following categories: size of offset (area), species biomass or productivity, special habitat features or suitability, biological requirements (e.g., prevention of invasive species settlement in newly restored or created habitat), or preservation (e.g., banking). Sometimes implementation of a monitoring program was required. With mitigation banking, the expected ecosystem impact was offset by purchasing credits from a habitat bank (Burgin 2008). Although habitat banking is often mentioned alongside traditional offsetting schemes, it does not follow the same principle because most banks preserve already existing habitat. In policy and practice, this is not the same as enhancement, restoration, or creation, which presents a different philosophy in the initial goal of achieving not net loss. Due to these differences and a smaller sample size of banking offsets ($n = 50$; all in the United States), we excluded banking projects from the analyses (final $n = 577$).

There were a multitude of compliance-related metrics and targets used to stipulate desired offsetting outcomes. First, offsetting area requirements (commonly North America) entails the physical area that must be replaced to adequately offset the expected habitat loss. Offsetting area was generally specified in the permit and evaluation files, obtained from government agencies, which allowed for comparison. (See Supporting Information for data origin.) Second, many permit requirements explicitly state the replacement target of lost species biomass and productivity (NNL) (Harper & Quigley 2005*b*). Calculations for biomass and productivity are commonly done under the premise of maximum ecosystem natural capability (Stebbing 1992; Langton et al. 1996; Minns 1997). Third, special requirements can often be found in offsetting permits, where conditions ranged from the construction of a specific habitat to the reduction of invasive species. Last, compliance for some projects was also linked to monitoring programs. In those cases, a postconstruction monitoring program was to be set up and data were collected through subcontractors.

Like *compliance*, *function* is a broad term, defined by an overall assessment (e.g., rapid assessment methods [RAM]), single factors (e.g., water quality), NNL of species diversity, or enhanced habitat features (e.g., shelter construction in spawning area). Function was assessed by government agencies or researchers associated with the project or evaluated as part of an independent scientific study. A RAM was often used to quickly assess a broad array of ecosystem functions for wetlands and provided a summary measure of an ecosystems' state (Carletti et al. 2004; Fennessy et al. 2007). Function was also assessed on single factors, such as hydrogeomorphological aspects (e.g., flow velocity of a river after riprap construction) (e.g., Brinson 1998) or specific chemical processes (e.g., nitrogen retention in restored wetlands) (e.g., Craig et al. 2008). Species-dependent ecosystem functionality was mostly measured through biomass and productivity replacement. Ecosystem function was also evaluated based on whether actions enhanced the ecosystem. In this category, constructed habitat features were assessed regarding their integrity and benefit provision.

Common Metric for Compliance and Function

To allow for objective comparisons among projects, we converted project characteristics into common metrics: project size, management target (e.g., habitat based and productivity based), methods used (e.g., restoration and enhancement), and location and ecosystem type (e.g., wetland and lake). Projects that had a 2-dimensional footprint were converted into hectares. In contrast, the majority of riverine project information (streams and rivers separated by stream order as a measure of relative stream size: stream, ≥6; river, <6 [Supporting Information]) was provided on a 1-dimensional scale (e.g., enhancing 500 m of river stretch) and converted to kilometers. Project were classified as small (<0.5 ha/km), medium (0.5–5 ha/km), or large (>5 ha/km). Furthermore, we assigned each project one or more project targets (habitat, productivity, and function) based on source material.

We assigned compliance and function scores to each project and converted the scores into integers. Compliance scores ranged from 0 to 3 (0, noncompliance, 0–25% of requirements met; 1, partial compliance, 25–90% of requirements met; 2, full compliance, 90–110% of requirements met; 3, overcompliance, >110% of goals met). Function scores (ranged from 0 to 2 (0, no functionality, 0–25% of ecosystem properties functioning as desired; 1, partial functionality, 25–90%; 2, full functionality, >90% of declared targets met). Overfunctionality was not considered in project assessments because maximum ecosystem function unlike compliance cannot be surpassed. The large margin for partial compliance and function was chosen due to high project uncertainty and variation in requirements and assessments across projects (see Supporting Information). An error margin of 10% was included, which is applied in most permits (e.g., meeting 90% of the permit requirements or assessment criteria were accepted as full compliance or full functionality).

The following from an official evaluation report (Ambrose et al. 2007) provides an example of how project information was translated into compliance and function scores (Supporting Information). The extension of Newport Coast Drive in California led to the functional loss of 0.58 ha of wetlands. The official permit required creation of 2.30 ha of new wetlands and revegetation with native plants. Compliance results showed that 2.42 ha of new wetlands were created, and the revegetation of native plant species was successful. The newly created wetlands were 105% of the required offsetting project size and fell into the 90–110% margin. This project received a score of 2 (i.e., full compliance). Revegetation, stated as successful, received a full compliance score as well. The mean compliance score was 2; thus, we deemed the project as fully compliant. An independently conducted scientific evaluation of the same project was assessed for ecosystem function based on a RAM. The official RAM score was 63.19 out of 100. This score indicated that not all assessed ecosystem aspects were functioning as required to reach full function (>90). Accordingly, we assigned the project a function score of 1 (partial functionality). This scoring method was applied to all 577 projects. Two sample assessments are provided in Supporting Information.

Data Analyses

First, we determined whether ecosystem-function scores were dependent on the assessed level of compliance (Supporting Information) with a permuted analysis of variance (perANOVA) from the car package for R software (Fox et al. 2017) and pairwise *t* tests to identify individual significant effects. We chose perANOVA because it has a nonparametric design and data for compliance had a nonnormal distribution (Anderson 2001). Adjustments for multiple testing were completed following Holm (1979). The Holm (or Holm–Bonferroni) correction counters the possibility of underclaiming significant pairs and groups (Holm 1979; Aickin & Gensler 1996). Results were presented as a 2-way frequency bar graph to highlight the integer ratings of the common metric for compliance and function.

Second, we determined whether compliance and function differed based on scale of the project and the 3 possible project targets (habitat, basic function, and productivity). (See Table 1 for descriptive statistics.) For this we used a permuted linear model and perANOVA. The permuted linear model was completed first to determine whether there were possible significant effects of project location (country), system (river, stream, lake, and wetland), project size (small, medium, and large), number of project targets, and number of offsetting methods used on the response variables' compliance and function. The perANOVA was completed for the linear permuted model and tested for all 5 factors and possible interactions (i.e., compliance (function)~location * system * scale * method number * target number) (car package for R; Fox et al. 2017). The permuted design was chosen and applied to both the compliance and function model to generate comparable means (Anderson 2001). A Scheffé (1960) test for compliance and function was conducted post hoc to determine significant differences for pairwise comparisons. We used cumulative percentage bar graphs to present results so as to stay truer to the original integer ratings.

Finally, a second permuted linear model and perANOVA were used to investigate the effect of specific project targets (habitat, productivity, and basic function) and type of offsetting method (creation, restoration, and enhancement) on project outcome (positive or negative) (visualized using stacked bar graphs). Proportional project distribution across aquatic systems (rivers, streams, lakes, and wetlands) was calculated for Canada, Europe, and the United States. Analyses were completed using R statistical software (R Core Team 2013) version 3.4.2 (packages used: Car, lsmeans, multcomp, ggplot2, tidyr, gridExtra, and dplyr). The null hypothesis was rejected when $p < 0.05$ and not rejected when $p > 0.05$. Results are reported as $p < 0.05$ when p was 0.001–0.05 and results <0.001 stated as $p < 0.001$.

Results

Cross-Country Relationships for Compliance and Function

Function increased gradually (for all locations [see Supporting Information]) as compliance scores increased ($p < 0.001$) until both scores leveled out when overcompliance was reached (score 3, $p = 0.53$) (Fig. 2 & Supporting Information). Overall, function scores were lower than compliance scores (Table 1). Function increased with project size (df $= 2$, $p < 0.05$) (Fig. 2 & Table 2). Location, system, scale, and number of project targets, but no interaction terms, affected function scores significantly (df $= 2$, $p < 0.05$) for offsetting projects (Table 2). Location and system, but no interaction terms, were also significant factors for compliance (df $= 2$, $p < 0.05$).

Compliance

Among ecosystem types, compliance was the highest for river and lake projects (two-thirds of projects had full or overcompliance, mean score [SD] 1.81 [0.78] and 2.00 [0], respectively) and was significantly higher relative to wetland projects (mean 1.38 [0.98]) (Fig. 3a). Approximately 50% of wetland projects achieved compliance levels of 0 or 1 (Fig. 3a). Projects incorporating streams did not differ significantly from the other systems (Fig. 3a). Mean compliance was not significantly different among project scales and targets. Regionally, Canada had the highest compliance scores (mean 1.78 [1.18], 25% of projects were overcompliant), which were significantly higher than projects in the United States (mean 1.41 [0.91]) (Fig. 3a). Europe did not differ significantly in compliance from either Canada or the United States, although it had higher compliance than U.S. projects and the fewest projects with a compliance score of 0 (mean 1.71 [0.62]) (Fig. 3a).

Function

Riverine projects had the highest function scores (mean 1.55 [0.6], ~60% achieved full-function score) and were significantly higher than stream and wetland projects (mean 1.28 [0.6], 1.05 [0.65]) (Fig. 3b). Projects in Canada and Europe had significantly higher functionality

Table 1. Mean compliance (C) and function (F) scores for offset project targets of species productivity, habitat features, and basic ecosystem function in 577 projects.

	Productivity		*Habitat*		*Basic function*	
Project scale	*C (SD, n)*	*F (SD, n)*	*C (SD, n)*	*F (SD, n)*	*C (SD, n)*	*F (SD, n)*
Small	1.77 (0.59, 36)	1.33 (0.73, 36)	1.78 (0.75, 41)	1.53 (0.62, 30)	1.45 (0.99, 209)	1.07 (0.68, 166)
Medium	1.78 (0.72, 47)	1.65 (0.53, 35)	1.49 (0.79, 55)	1.55 (0.61, 47)	1.40 (0.86, 208)	1.25 (0.59, 137)
Large	2.18 (0.75, 16)	2.00 (0, 13)	1.66 (0.88, 12)	1.81 (0.40, 11)	1.55 (0.90, 40)	1.38 (0.63, 50)

Note. Multiple targets may be present in a single project.

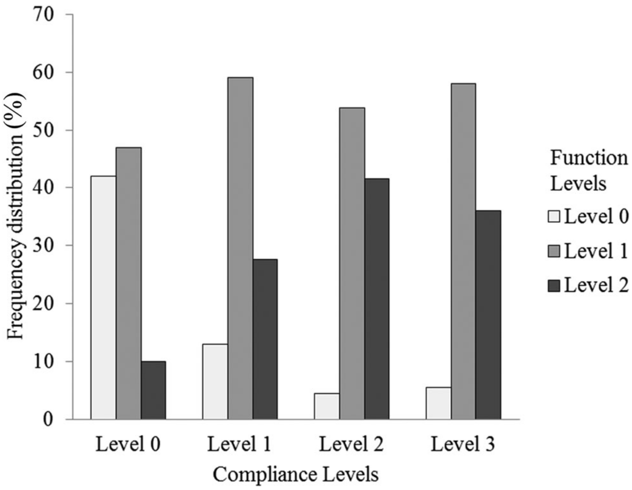

Figure 2. Frequency distribution of function of ecosystems (0, nonfunctional; 1, partially functional; 2, fully functional) and level of compliance with permits (0, noncompliant; 1, partially compliant; 2, fully compliant; 3, overcompliant) in 577 biodiversity offsetting projects.

Table 2. Analysis of variance model results for ecosystem function and compliance with permits in regards to location, system, scale, offsetting methods, and offsetting project target.

Add label	*df*	*Sum of squares*	*Mean square*	*F*	*Pr(>F)*
Function					
location	3	22.27	7.423	20.752	<0.001
system	3	4.38	1.461	4.084	0.007
scale	2	2.95	1.477	4.130	0.0168
number of targets	2	6.05	3.027	8.462	<0.001
Residuals	405	144.87	0.358		
Compliance					
location	3	8.4	2.8144	3.498	0.0154
system	3	8.4	2.8150	3.499	0.0154
residuals	546	439.3	0.8046		

*Note. Nonsignificant factors and interactions removed from the model (initial model: function (compliance~location*system*scale*target number*method number). Nonsignificant factors as part of a significant interaction are in the model. Linear permutated model design was used for nonlinear distribution of data.*

(mean 1.59 [0.51], 1.55 [0.62]) than projects in the United States (mean 1.07 [0.44]) (Fig. 3b). Lakes had high function scores associated with offsetting projects as well (mean 1.5 [0.55]), but a low sample size (n = 6). Small projects had significantly lower function scores (mean 1.09 [0.63], 20% with ecosystem function 0) than medium or large projects (mean 1.28 [0.62], 1.4 [0.69]) (Fig. 3b). Mean function scores increased significantly as the number of management targets increased (Fig. 3b). Function was lowest for projects with a single target (mean 1.10 [0.65]) and increased in projects with 2 (1.35 [0.61]) (Fig. 2b) or 3 (mean 1.79 [0.41]) (Fig. 3d) different targets.

Specific Management Targets and Methods

Both compliance and function were significantly higher (mean 1.75 [0.69], 1.53 [0.64], $p < 0.05$) in projects that took a productivity approach compared with those that did not (mean 1.41 [0.95], 1.13 [0.64]) (Figs. 4a & 4b). Habitat-based project approaches also had a positive influence on function ($p < 0.001$); over 60% of these projects achieved full ecosystem functionality (Fig. 4a). Projects focusing on basic function replacement had a lower proportion of projects in the higher compliance and function levels and consequently lower overall mean compliance (mean 1.43 [0.02] vs. 1.77 [0.75]) and function scores (mean 1.2 [0.65] vs. 1.39 [0.69]) (Figs. 4a & 4b). Including restoration measures in a project increased the mean function score (mean 1.38 [0.64] vs. 1.06 [0.64]) of projects compared with projects without restoration ($p < 0.05$). Projects with any form of habitat enhancement were less likely to be noncompliant (level 0, 12% vs. 22%, $p < 0.05$). Function (mean 1.05 [0.61] vs. 1.37 [0.66]) and compliance (mean 1.37 [0.98] vs. 1.64 [0.77]) were significantly lower ($p < 0.05$) for offsets that created entirely new habitat or whole ecosystems (Figs. 4a & 4b) than offsets that restored or enhanced existing habitat or ecosystem features.

Canada, the United States, and Europe differed in their project management targets and methods. Enhancing existing ecosystems was used equally in the United States and Europe (Figs. 5e & 5f). Habitat creation was more common in Canadian and U.S. projects (57.8% and 62.8%, Figs. 5d & 5e) than in European projects (14.3%, Fig. 5f).

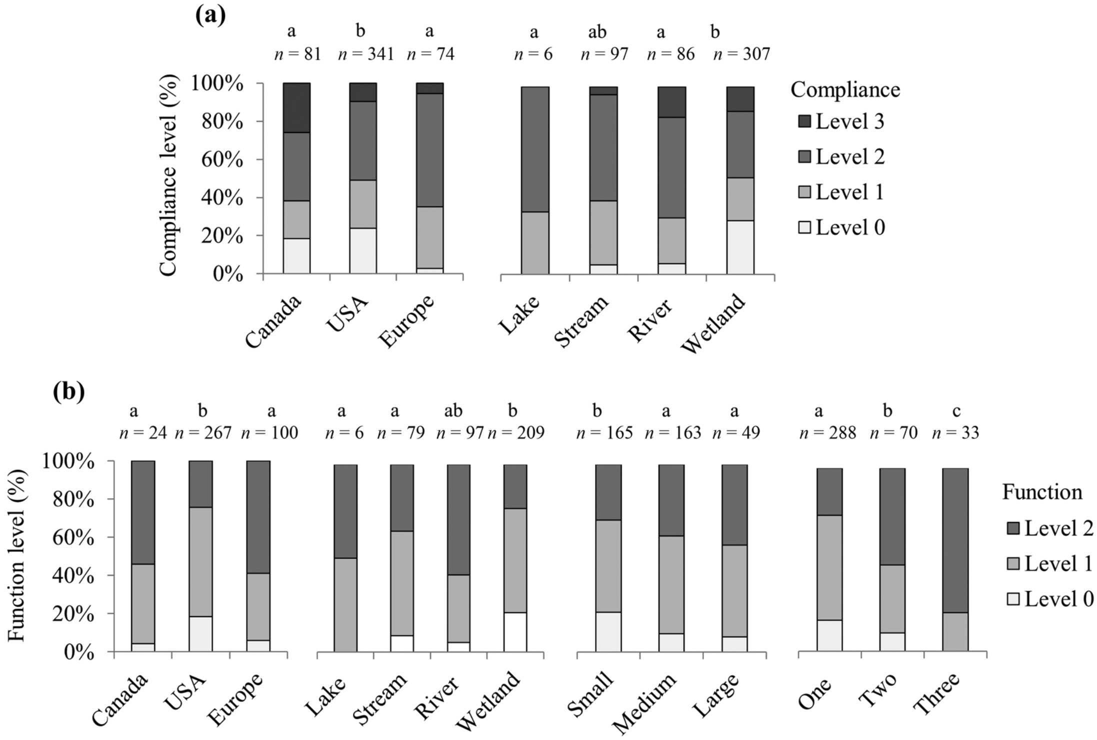

Figure 3. Cumulative percentage of biodiversity offsetting project (a) compliance with permits and (b) function of ecosystems. Project factors include region, project system (river, lake, stream, and wetland), project scale, and number of project targets from among species productivity, habitat, and ecosystem-function targets. Significant differences in mean compliance and function levels (Scheffé test) have different letters in each group (a, b, and c).

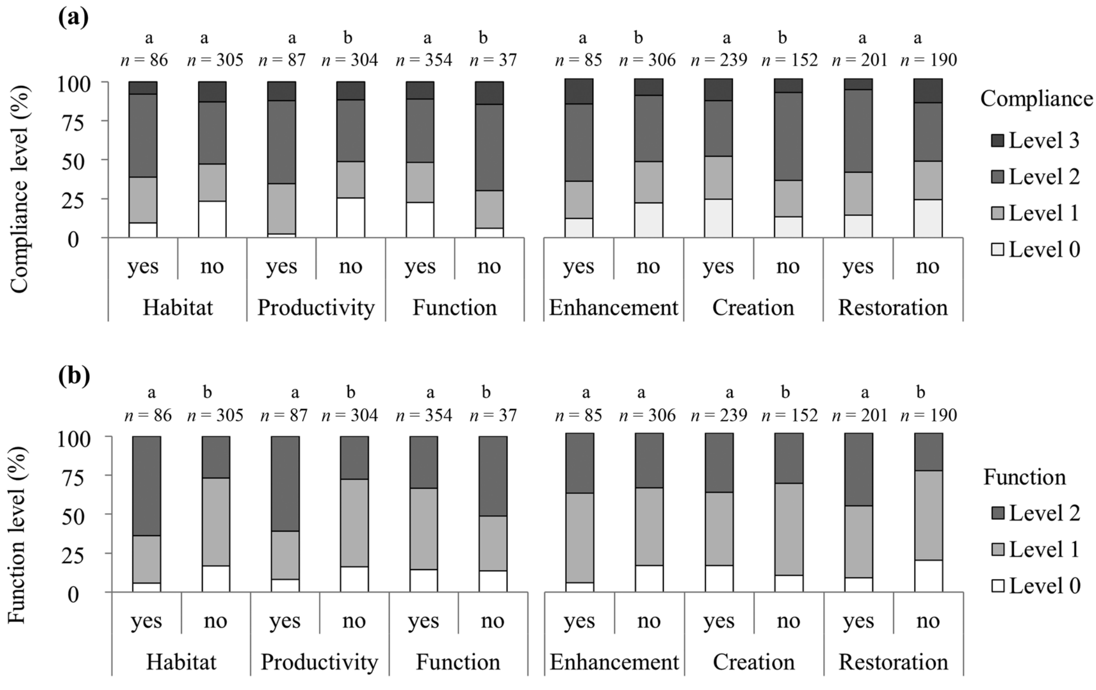

Figure 4. Cumulative percentage of offsetting project (a) compliance with permits and (b) function of ecosystems by target type (species productivity, habitat, and ecosystem function) and offsetting method (creation, restoration, and enhancement). Significant differences in mean compliance and function levels (Scheffé test) have different lowercase letters in each group (a and b).

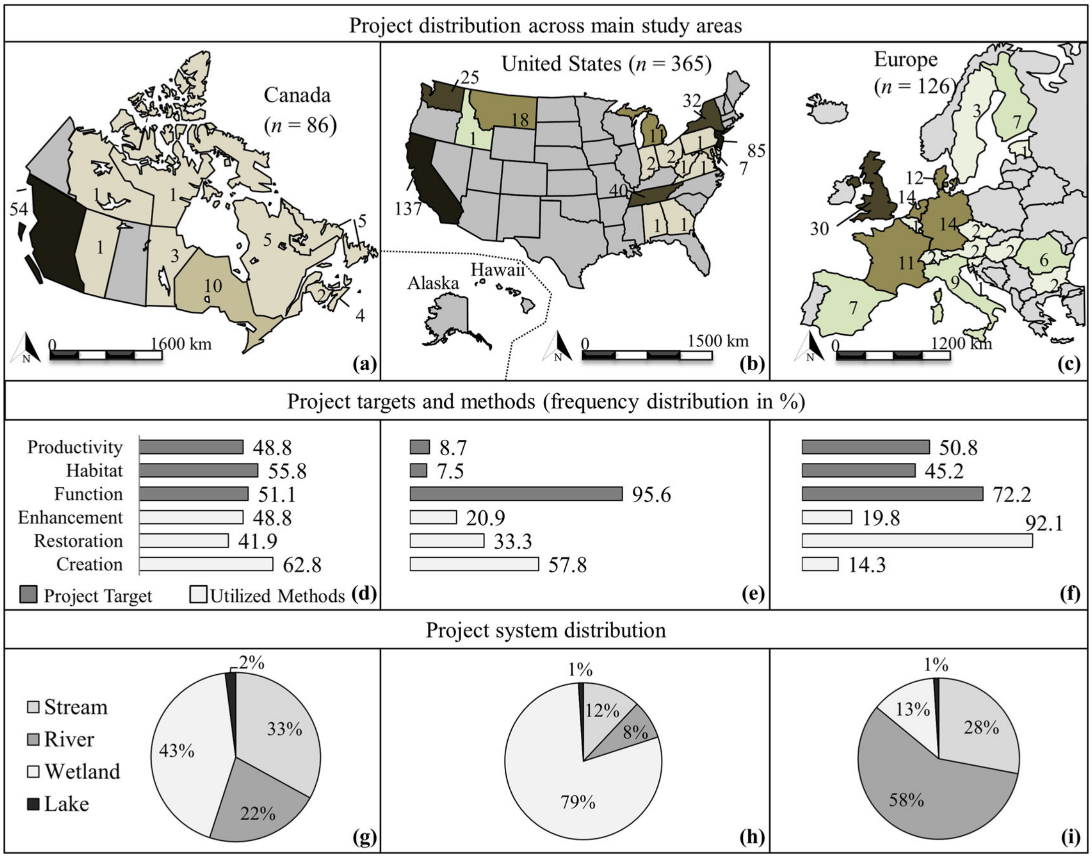

Figure 5. Regional offsetting project (a–c) density distribution; (d–f) targets (species productivity, habitat suitability, or ecosystem function) and offsetting measures (individual projects can contain several targets and measures) (proportional bar graphs); and (g–i) types of aquatic ecosystems in which offsetting projects were implemented for Canada, United States, and Europe.

We also found that 33.3% of United States and 41.9% of Canadian projects implemented habitat restoration measures (Fig. 5d & Supporting Information), whereas restoration efforts were widespread in Europe (92.1% of projects) (Fig. 5f). Function-focused approaches were present in 95.6% of the U.S. projects, 72.2% of Canadian projects, and 51.1% of European projects. Productivity and habitat were equally part of around half of the Canadian and European projects but part of in <10% of U.S. projects (Figs. 5d–f).

Offsetting Ecosystem

Canadian projects were most commonly associated with running waters (33% streams, 22% rivers), followed by wetlands (43%) (Fig. 5g). The vast majority of assessed projects in the United States were wetland related (79%); rivers (8%) and streams (12%) made up the remainder (Fig. 5h). European projects were predominately located in rivers (58%) and streams (28%); only 13% were wetland related (Fig. 5i). Lakes (no usable case study data found for reservoirs) were underrepresented in all 3 regions (<2%).

Discussion

Many projects we considered were officially labeled a success because compliance linked to legislative requirements was high. This hints at a probable bias in the published literature toward projects that were considered successful. We tried to reduce this bias by including all available literature, ranging from official reports to reports on evaluations conducted several years after construction. Although they may foster increased ecosystem functionality, compliance and function are not equivalent because they are based on different criteria and motivations in achieving ecosystem function (Kentula 2000; Kozich & Halvorsen 2012). Our findings demonstrate the advantages of incorporating more ecosystem-related aspects into legislative and regulatory tools to ensure proper implementation and acknowledging apparent ecological constraints and ecosystem limitations. Our results suggest compliance cannot be treated as equivalent to ecosystem function; offsetting projects benefit from increased ecosystem function when several, complementary management targets are in place; offsetting projects benefit from increased ecosystem function in larger projects; and creating novel ecosystems have underestimated challenges and uncertainties and thus lead to a higher risk of failure.

Compliance

Offsetting compliance was affected by project system type and location (or geographic position). Lower compliance in wetlands appeared to be directly related to permit goals and requirements. For example, for many assessed studies in this synthesis and other literature, wetland permits often include criteria that may be difficult to achieve or that underestimate dynamics, which leads to reduced compliance and increased failure (e.g., Allen & Feddema 1996; Bendor 2009; Quétier & Lavorel 2011). A similar effect was observed for criteria that did not provide the proponent with clear guidance (Brown & Veneman 2001; Matthews & Endress 2007). This may be related to a lack of knowledge and misunderstanding on the proponent's part or ambiguity within the permit and shortcomings or loopholes in the legislation or framework (Brehm & Hamilton 1996). Finally, low compliance in wetland projects may be directly linked to functionality issues with creation of new ecosystems and wetlands in general (underestimated system) and to proponent's ability to meet requirements (Brown & Veneman 2001; Matthews & Endress 2007; McKenney & Kiesecker 2010). Geographic-dependent differences in compliance are partially a consequence of different offsetting frameworks and partially due to regional differences in the ecosystem types used for offsetting projects. The United States had a high proportion of wetland projects assessed in this synthesis (Fig. 5) that were less compliant than projects in other systems (Fig. 3).

In addition to project-related factors, external influences are important for compliance. Many European offsetting projects are embedded in the Natura 2000 framework (Ostermann 1998; Weber & Christophersen 2002). This regulatory framework encourages restoration approaches and perpetual project duration (McKenney & Kiesecker 2010), which could ensure higher and longer lasting compliance, which aligns with goal-framing theory (Sunstein 1996; Etienne 2011). Although the mitigation system in the United States has a strong basis under Section 404 of the Clean Water Act, backed by the 1990 Memorandum (Hough & Robertson 2008; McKenney & Kiesecker 2010), the theory and practices differ. The equivalence, location, timing, duration, and offset ratio factors are comparable to other mitigation systems, but many states have developed their own offsetting systems and ratios with a focus on area replacement. These between-state differences (Brown & Venenman 2001, Matthews & Endress 2007) combined with administrative shortcomings (Turner et al. 2001; Matthews & Endress 2007) potentially lead to reduced compliance in offsetting projects in the United States.

Function

One of the main aspects often considered in ecosystem-based offsets is size and scale (Peterson et al. 1998; Palmer et al. 2010). Large projects had significantly higher functionality than small projects (Fig. 3). One reason for this is the inability of small systems to become resilient. For instance, if a project in a small system fails, it often fails completely, whereas larger systems may have greater capacity and resiliency to offset for partial loss of function (Jähnig et al. 2010; Mant et al. 2016). Also, function in small projects may be impaired by catchment-related degradation and unaddressed broad-scale pressures like water quality or connectivity beyond the scope of the offsetting project (e.g., Jähnig et al. 2010; Bernhardt & Palmer 2011). Also, more detailed and careful planning processes are often evident in larger projects (Brown & Veneman 2001). This may explain the lower functionality of stream versus river-based projects. Offsetting functionality is also system dependent; high offset function in river projects had the highest offset function and the wetland projects the lowest (Fig. 3b). There are 2 possible explanations for low functionality in offsetting wetlands. First, wetland restoration or creation is difficult because it draws on complex interactions of landscapes, different aquatic and terrestrial microhabitats, hydrological and soil properties, a vast array of chemical processes, and rarely follows the general principles of succession (Brown & Bedford 1997; D'Avanzo 1989). Further, wetland projects we assessed were often newly created ecosystems (64.3%), whereas riverine projects mostly relied on restoration and enhancement of existing systems. Enhancement and restoration had strongly positive effects on function, whereas creation led to lower functionality relative to the other 2 methods.

Unsurprisingly, creating a new ecosystem had greater uncertainty than restoring an existing one. Ecosystem processes that involve nutrient cycling and food webs have to be established, and there is also a higher risk of introduction of invasive species during the assembly process (D'Avanzo 1989). This may explain the significant differences in success in ecosystem function between the United States and Canadian and European projects; 79% of U.S. projects involved wetlands in which a new ecosystem was created. In Europe, most projects were completed on riverine systems (86%) and relied heavily on restoration and enhancement, which resulted in good overall functionality. Although Canadian offsetting projects featured significantly higher functionality than U.S. projects, they still contained a large amount of wetland related projects (43%) and the creation of new systems (62.8%). Half of the Canadian projects focused on habitat specifications, productivity, or both. Only a minority (<10%) of U.S. projects considered those approaches, and most projects focused on basic-function replacement (95.6%). Basic-function replacement can be difficult because it often leaves out many species-related factors, habitat features, and physical interactions on an ecosystem and landscape scale (Whigham 1999). In these cases, long-term establishment of an ecosystem is still likely but will differ from natural, functioning systems (Scatolini & Zedler 1996).

Having multiple management objectives increased ecosystem function. Focusing on a single target approach, such as bolstering productivity through reestablished connectivity but disregarding habitat features, flow regime, and other factors, is unlikely to achieve full functionality for many species (Minns et al. 1996; Palmer et al. 2010). A multitarget approach would aim to reach "the least degraded and most ecologically dynamic state possible, given the regional context" (Palmer et al. 2005). A multitarget approach also holds the potential to reduce possible distortion of ecosystem productivity. For instance, high biomass by itself would not factor in fish community composition and habitat quality. A fish community with high biomass composed mostly of species of low trophic levels would most likely not be sustainable over the long term and would not include commonly desired target species on higher trophic levels (Carpenter et al. 2001; Gascuel et al. 2005; Ruppert et al. 2018). Thus, habitat offsetting projects appear to benefit functionally from complementary management targets. This is consistent with recent calls for offsetting projects to include multiple management targets that may improve long-term ecosystem function (Ruppert et al. 2018).

Relationship Between Function and Compliance Dependency

Overall a higher compliance score generally yielded higher ecosystem functionality. This weak relationship suggests compliance is important, but not sufficient in itself to achieve good ecosystem function. There also seemed to be a threshold to increasing function; overcompliant projects did not substantially increase functionality. This situation likely resulted for several reasons. First, there is likely an ecological threshold (e.g., carrying capacity) for each ecosystem, limiting the overall effect of offsetting methods. For instance, a constructed spawning area for salmonids can only raise productivity a certain degree, depending on the area's size and the ecosystem it is embedded in. Second, there may be unconsidered time lags (i.e., it may take longer for full functionality to be realized in projects; Minns 2006; Moilanen et al. 2009; Scrimgeour et al. 2014). Considering this underlines on the one hand the need for proper long-term monitoring programs and on the other hand inclusion of the most recent scientific advancements to estimate ecosystem limitations and dynamics and develop realistic timelines (Calvet et al. 2015). Finally, many assessed projects were overcompliant in targets, such as project size and biomass, which did not necessarily lead to increased function. This could also underline the fact that necessary components for enhancing habitat functionality are still poorly understood (Courtice et al. 2014). Higher levels of compliance could also be motivated by nonecological drivers that we did not assess. Those drivers are founded in strategic behavior theory, where overcompliance is often driven by competitive advantages and public image or linked to values and beliefs of upper management (e.g., Maxwell et al. 2000; Karpoff et al. 2005; Wu 2009).

Study Limitations

Conducting a scientific synthesis on such a large scale has limitations. First, pooling both peer-reviewed and gray literature may have led to uncertainty in data quality, despite critical appraisal strategies, and to a bias depending on which government agencies provided data. However, including gray literature may have reduced the bias of peer-reviewed literature mostly covering successful projects. Overall, using a common metric lowered information value in a trade-off between harmonized and comparable data. Finally, offsetting projects in large parts of the world were inaccessible due to language and may yield results different form North American and European projects.

Compliance seems to be a rather well-defined measurement in the form of permit requirements that may be influenced by administrative shortcomings rather than actual project specifications. Though often including criteria linked to ecosystem function, permits rarely encompassed a holistic ecosystem assessment, which made compliance a poor measurement for overall project function. Project planning and official permits should aim to encompass more ecosystem-function requirements. This approach, especially when done in a more holistic manner and covering different ecosystem aspects, would further strengthen the relationship between compliance and function when properly enforced and implemented. This in turn requires an increased consideration of scientific studies in advisory reports to be able to give proper advice for offsetting policies or to refine newer approaches, such as banking schemes and commoditization of conservation efforts (e.g., Reid 2011; Mann 2015). Ecosystem functionality can be harder to assess and evaluate because no clear guidelines exist on what should be included and which method should be used. This uncertainty is emphasized by higher function levels being harder to achieve via creation of new ecosystems, especially wetlands, relative to restoring or enhancing existing systems. Bigger projects often hold more potential to achieve higher ecosystem function than smaller ones. Furthermore, the inclusion of multiple management targets improved ecosystem function, underlining the need for more ecosystem-based approaches in offsetting projects to ensure long-term stability and resilience. Lakes as means to offset environmental losses were highly underutilized and hold potential for future offsetting projects, especially considering the global abundance of reservoirs and abandoned mining and gravel pits (e.g., McCullough & Lund 2006; Gammons et al. 2009; Ruppert et al. 2018). Considering the variability in offsetting projects, it remains vital to increase knowledge and develop management plans on a project-by-project basis to help develop a broader, general framework that can aid in providing guidance and support. Although it is encouraging that compliance and function are positively related, policy and practice should strive to strengthen this relationship to realize long-term goals of offsetting projects, such as healthy and sustainable ecosystems.

Acknowledgments

Funding for this project was provided by Mitacs Cluster Accelerate (RES0027784) and Converge (RES0021639) grants to M.P. Industry support was provided by Canadian Natural Resources Limited (CNRL).

Supporting Information

Synthesis protocol (Appendix S1), additional references (Appendix S2), function and compliance in relation to location (Appendix S3), and positive and negative effects of project targets and methods (Appendix S4) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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