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In-Lieu Fee Credit Allocations on Public Lands in the United States: Ecosystem Prioritization and Development-Driven Impacts

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Abstract

In-Lieu Fee programs are an important mechanism for compensatory mitigation in the United States and received wide-spread standardization after the regulatory mitigation rule change of 2008. On public lands, they are especially important for pooling funds from numerous small-scale impacts that might otherwise go unmitigated. This study examines the use cases of fee program credits on public lands since 2008. Using data from the Regulatory In-Lieu Fee and Bank Information Tracking System, I analyzed eleven active In-Lieu Fee programs approved post-2008 across 78 service areas, encompassing 1043 credit transactions. Transactions were categorized by credit amount, proportion, target ecosystems, and impact designations. The analysis highlights the influence of residential and commercial development, alongside resource extraction, as major contributors to fee program transactions, underscoring the program's role in mitigating various development pressures. Residential, commercial, and government projects frequently co-occur within service areas, which can support policy planning to anticipate potential cumulative impacts and expected future impacts and credit demands. Furthermore, my analysis shows that impacts from resource extraction require proportionally larger offsets than those from residential or recreational activities. The findings suggest that programs on public lands can fill a niche distinct from mitigation banks, as they address a multitude of impacts while further allowing for the pooling of resources and funds from small-scale impacts, while the use of advance credits remains contentious for achieving no net loss.

Keywords: nature market; conservation; policy framework; regulator; development

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1. Introduction

Freshwater systems are disproportionately affected by habitat loss, invasive species, pollution, and overharvest, with cumulative and emerging stressors like microplastics further worsening their conditions [1–3]. In response, global conservation policies aim to slow biodiversity decline and safeguard critical habitats, recognizing the essential role of freshwater ecosystems for both ecological integrity and human well-being [4–8].

Negative impacts from land use or development projects both on private and public lands can be permanent or temporary. Proper project planning and approval processes can sometimes avoid, reduce, or reverse these impacts [9,10]. This has led to the establishment of the mitigation hierarchy, which requires developers to explore alternatives to avoid, minimize, or reverse negative impacts, with recent studies emphasizing a need for strengthening the avoidance step of the hierarchy [6,11,12]. When negative impacts are unavoidable,

they must be compensated through environmental offsets to achieve no net loss (NNL) of ecosystem services, habitat area, biodiversity, or more recently, net gain [13,14]. Offsets can be on- or off-site and can involve in-kind (similar to lost ecosystem aspects) or out-of-kind gains (different from lost ecosystem aspects), depending on feasibility, regulatory guidance, and legislation [14–17]. In terms of land use type, public lands tend to play a significant role in biodiversity conservation and resource management. Their extensive coverage and federal- and state-level governance structures mean that decisions about mitigation on public lands can have broad ecological and policy implications [18,19].

Alternative mechanisms like banking and In-Lieu Fee programs (ILFs; Figure 1) transfer the responsibility for offset establishment and management—the last step in the mitigation hierarchy—to a third party through a payment-based credit system, addressing habitat, ecosystem service, or biodiversity values while potentially providing more region-wide and interconnected funding vehicles for regulatory agencies [20–24].

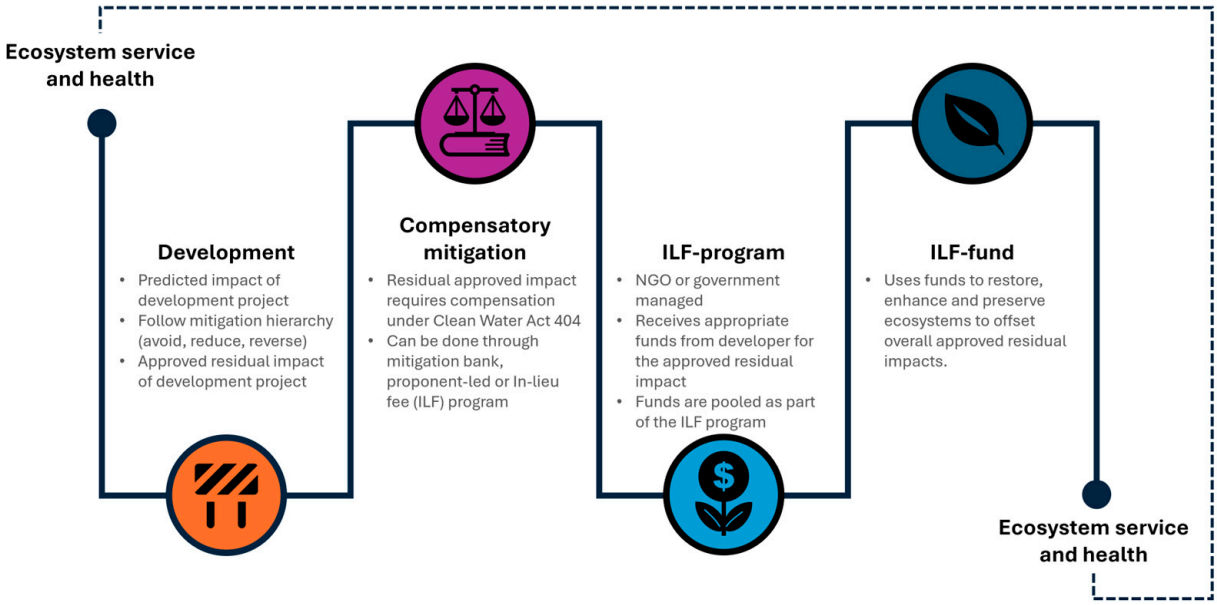

Figure 1. Theoretical overview on how In-Lieu Fee (ILF) programs operate under the Clean Water Act (404) in the United States as part of the overall compensatory mitigation policy [23–26]. Symbol attribution uxwing.com (accessed on 14 July 2025) and presentationgo.com.

In the United States, ILFs are often non-profit organizations or government bodies predominantly offering advance credits [23–26]. Said advance credits are also a major criticism of ILFs, since often at the time of credit sale, no physical and tangible offsets exist [23,25,27]. Moreover, using offsets to compensate for lost ecosystem functions or habitat area is often associated with long-term project underperformance, increasing the risk of failing to meet no net loss (NNL) or net gain targets [14,27–29]. Consequently, ILFs declined temporarily in popularity, with mitigation banks becoming the norm under the 2008 mitigation rule, which applies stringent and more uniform requirements for ILF approval and favors mitigation banks [26]. ILFs were mainly affected by the rule through more uniform, stricter standards pertaining to the mitigation hierarchy, financial assurances, detailed mitigation plans, monitoring and reporting, timing of mitigation, and increased public and stakeholder involvement [26].

Despite the changes, ILFs remain a large part of the mitigation market in the United States, currently making up 18% of all approved compensatory sites and 6% of all approved programs and banks (e.g., mitigation banks and conservation banks, as of February 2024), with some located on public lands [30]. While private and mixed ownership land

conservation is growing in interest, public lands still play a major role in conservation and mitigation policy, with around 650 million acres designated as public land [7,31,32]. These lands are managed by agencies such as the Bureau of Land Management, Forest Service, Fisheries and Wildlife Service, and National Park Service, which face concerns about ineffective management policies [18,19,31]. While compliance is one aspect of compensatory mitigation, application, and use cases are another important part. The role and use of ILFs on public lands and potentially future conservation use after the 2008 Rule remain largely unevaluated [8,33,34]. The objective of this study is to evaluate the types of environmental impacts being offset by ILF programs in the United States, focusing specifically on transactions from ILF programs approved after the 2008 Compensatory Mitigation Rule and situated on public land. This evaluation aims to understand the nature and scope of the impacts addressed by these ILF programs and the role ILFs play in the current mitigation landscape of the United States, with public lands potentially becoming more integrated into current mitigation networks in the future [35,36].

When it comes to ILF transactions on public lands in the United States, a central question is which sector is driving the offset impacts, with the literature commonly suggesting government activities, particularly in sectors such as transportation infrastructure and natural resource use given current and previous economic and social developments [37–39]. Specifically, this research is guided by the following questions:

1. To what extent are ILF transactions on public lands attributed to government versus non-government activities?
2. Which sectors (e.g., transportation, natural resource management) most frequently contribute to ILF transactions on public lands?
3. How do these patterns inform our understanding of public land use, resource allocation, and long-term mitigation planning?

Addressing these questions matters for three key reasons:

Resource allocation and policy: If government activities are confirmed as primary contributors, it may underscore the need for targeted policy or regulatory adjustments. For instance, transportation or resource management agencies might need to invest more heavily in sustainable practices or mitigation planning to reduce their environmental footprints on public lands.

Understanding public land use: Public lands are often managed with dual goals of conservation and sustainable resource use. Knowing that and how certain government activities drive a substantial proportion of ILF credits could inform strategies to balance these objectives, helping to preserve ecological value in high-use areas.

Future ILF demand and planning: Government-driven ILF transactions on public lands could predict future demands for mitigation in specific areas, helping ILF providers and agencies plan for long-term resource needs and ecological goals.

This set of research questions can collectively highlight how government-driven ILF transactions on public lands intersect with broader U.S. land management policy by potentially revealing the need to align resource allocation, regulatory adjustments, and long-term mitigation planning with the dual mandate of conserving ecological value while supporting sustainable public land use.

2. Materials and Methods

I used the Regulatory In-Lieu Fee and Bank Information Tracking System (RIBITS) to gather data on ILFs on public lands. Data and the linked ILFs were scanned through a keyword search using the slowraker package (v0.1.1) in R [40]. I scanned the whole extent of ILFs (n = 106) and associated files on RIBITS as of 3 February 2024. In-detail

reviewed ILFs pertained directly to active and approved programs on public lands, with an approval date after the 2008 Rule (n = 11 across 78 service areas). For this study, public lands were operationalized by searching for ILF program documentation in RIBITS that explicitly stated jurisdiction by federal, state, or local government land management agencies. Programs operating exclusively on private lands without a clear public nexus were excluded. Of the 106 active ILF programs listed in RIBITS as of February 2024, the selection was narrowed to 11 based on the following explicit criteria: (1) the program instrument must have been approved after the 2008 Mitigation Rule to reflect modern standards; (2) the program's service area must be situated primarily on public lands as defined above; and (3) the program must have a publicly accessible ledger with sufficient transaction detail to categorize impacts and ecosystems. Programs were excluded if they were inactive, approved before 2008, or lacked transparent transaction data. Credit transactions for each of the 11 ILFs were extracted to allow for an assessment of the targeted ecosystem and the designated impact the credit is meant to compensate for (n = 1043). All search and information reviews were conducted between February 3rd and 26 March 2024.

2.1. Categorization of In-Lieu Fee (ILF) Program Transactions

The extracted data was organized into distinct variables, as outlined in Table 1. Each variable serves to describe key aspects of ILF transactions, facilitating comparative and regional analyses. Credit amount and credit proportion provide quantitative insights into the scale of individual transactions, while impact designations and target ecosystems characterize the types of environmental impacts addressed. Location, sponsor, and jurisdictional data offer insights into regional administration and regulatory environments, while service area defines the geographic relevance of mitigation efforts. By systematically categorizing these variables, I aim to provide a comprehensive understanding of the ILF programs, their implementation, and the types of environmental impacts they address.

Table 1. Description of variables used in the analysis of In-Lieu Fee (ILF) transactions. The table provides details on key variables, including the credit amounts and proportions, classifications of impact categories, geographic and jurisdictional contexts, as well as ecosystem targets and service area definitions. Impact categories are abbreviated as follows: Road and bridgework (RB), residential development (RD), commercial development (CD), resource extraction (RE), recreational (RC), mixed-use development (MD), other or undefined (Other), and government use (GV). Ledger information available from RIBITS. Full variable definitions can be found in the appendix and dataset.

Variable	Definition
Credit amount	Represents the raw credit amount per transaction, indicating the number of credits issued for each ILF transaction.
Credit proportion	Indicates the proportionate credit amount relative to the total credits of the associated ILF program, contextualizing transaction scale.
Impact categories/ types	Classifies impacts by the nature of the activity. Road and Bridgework (RB) Residential Development (RD) Commercial Development (CD) Resource Extraction (RE) Recreational (RC) Mixed-use development (MD) Other or undefined (Other) Government use (GV)

Table 1. *Cont.*

Variable	Definition
Location	Identifies the state in which each ILF program operates, providing geographic context for regional analysis.
Sponsor	Lists the entity managing the ILF program, which may be non-profits, government agencies, or conservation groups.
Land jurisdiction	Specifies the governing entity with jurisdiction over the land involved, categorized as federal, state, local, or other.
Target ecosystem/credit type	Specifies the ecosystem or type of credit targeted by the ILF program, such as wetland or stream, and sub-types (wetland-general, wetland-tidal, wetland-seagrass, stream).
Service area	Defines the geographic area where impacts must occur to qualify for compensation, ensuring the ecological relevance of the impacted area.

2.2. Analyses

2.2.1. Transaction Distribution

To illustrate the flow of ILF credits across ecosystems and credit types, I used a Sankey diagram, which effectively displays the relationships between categories through frequency flows. The diagram shows the movement of credits from their originating ecosystems (wetlands, streams) over sub-ecosystems (wetland–general, wetland–tidal, wetland–seagrass, stream) to specific credit types across the ILF programs (ggplot2 v3.5.1; [41]).

2.2.2. Proportional Differences

To examine the proportions of credit transactions across different ecosystems and credit types, while controlling for program-specific variability, I employed a beta mixed-effects model [42]. To ensure meaningful comparisons, I scaled the proportions of each transaction relative to the total transaction amount within each program, as differences in units and metrics across programs prevent direct comparison (credit proportion). This program-specific scaling allows for consistent, interpretable proportions while respecting the credit scales used in different programs. Since my proportion data ranged from 0 to 100, I first transformed these values to fall within a [0, 1] range by dividing each proportion by one hundred. The transformation makes the credit proportion bounded between 0 and 1, a data structure for which the beta distribution is specifically suited. This approach is preferable to alternatives like a logit-transformed linear model because it directly models the heteroscedasticity inherent in proportional data without requiring transformation of the response variable, which can distort interpretations as well as offers more robust ways to manage uneven observations or missing data. Furthermore, it allows for the inclusion of random effects, compared to standard beta regression [42,43].

I fit the model using the glmmTMB package (v1.1.10), specifying target ecosystem and impact categories as fixed effects to test for differences across these categories. I included the ILF program as a random effect to control for potential variability among programs, thus accounting for repeated measures within each program [44]. The model was specified as follows:

Credit proportion $\sim$ target ecosystem + impact categories + (1|ILF program), with stream being the ecosystem reference and CD being the impact type reference within the model. The stream ecosystem is one of the two most common credit types, providing a

robust baseline for comparison. Commercial development (CD) represents a standard, moderate-scale development type, allowing for clear interpretation of the effects of both smaller-scale (e.g., residential) and larger-scale (e.g., resource extraction) impacts.

This approach enabled me to assess differences in credit proportions across ecosystem and credit types, while effectively controlling for program-level effects. Model diagnostics, conducted using residuals, confirmed that model assumptions were adequately met and no overdispersion occurred [42,44]. The model aligns with my objective to identify patterns in ILF credit allocation across ecosystems and impact categories, assessing if government-driven activities (e.g., transportation or resource use) on public lands significantly influence the distribution of credits across these categories.

2.2.3. Co-Occurrence of Impact Categories and Ecosystem Types

To evaluate the likelihood of different impact categories co-occurring within service areas and across target ecosystem, I conducted coincidence analysis. I constructed a bipartite co-occurrence network using the netCoin package (v2.1.9; [45]). Case study data were collapsed into unique service area impact and ecosystem type pairs, and their occurrence frequencies were used to create a weighted presence–absence matrix. Nodes in the network represented impact categories and target ecosystems services, with edges weighted by the co-occurrence frequency [46].

I applied Haberman's z-test for standardized residuals to test whether observed co-occurrences deviated from expectations under independence, retaining only associations with $p(Z) < 0.5$ ($n = 305$ transactions), which is appropriate for the exploratory analysis of a sparse dataset, suggesting probable coincidence between two categories when their conditional probability is greater than 50%. Degree centrality was calculated to quantify the number of direct connections each impact type and target ecosystem had, identifying highly connected nodes [47].

To detect clusters within the network, I used the Leiden community detection algorithm (leidenbase v0.1.35; [48]), which provides good accuracy and resolution, particularly important for small- or moderate-sized datasets compared to other clustering approaches like the Louvain algorithm. While Louvain is widely used, the Leiden algorithm improves upon it by guaranteeing that communities are well-connected and avoiding the issue of resolving into poorly connected or internally disconnected clusters, which is critical for small, complex datasets [49]. To identify key relationships and credit pathways, I recued network complexity further by only considering the lowest 33% of $p(Z)$ values from the network for the clustering algorithm, to ensure that identified clusters were based only on the strongest co-occurrences [48,50]. Together, the network and clustering approach enhanced the reliability of inferred co-occurrence patterns and improved the ability to detect meaningful insights from a small, complex dataset. Statistical outputs for each analytical step can be found in Appendix A.

3. Results

3.1. Credit Transactions

In total, I documented 1043 ILF credit transactions across various ecosystem types and impact categories. Wetland-related credits were the most prevalent, comprising 753 transactions (72%), of which 371 were categorized as general wetland (36%), 351 as tidal (34%), and 31 (3%) as seagrass. Stream ecosystems accounted for the next largest share, with 290 transactions (28%). When examining credit types, RD represented the largest allocation, totaling 431 transactions (41%), with GV only making up 9% of all ILF transactions on public lands (93 transactions). RE impacts on public lands were linked to 204 transactions (20%), and CD to 180 transactions (17%). Road and bridgework activities contributed

104 transactions (10%), while MD and RC were smaller contributors, accounting for 16 (1.5%), and 11 (1%) transactions, respectively (Figure 2). Four wetland transactions could not be linked to a specific impact (0.4%) and were labeled as 'Other'. The results indicate that impacts on wetland and stream ecosystems in ILF transactions are linked to residential development and resource extraction.

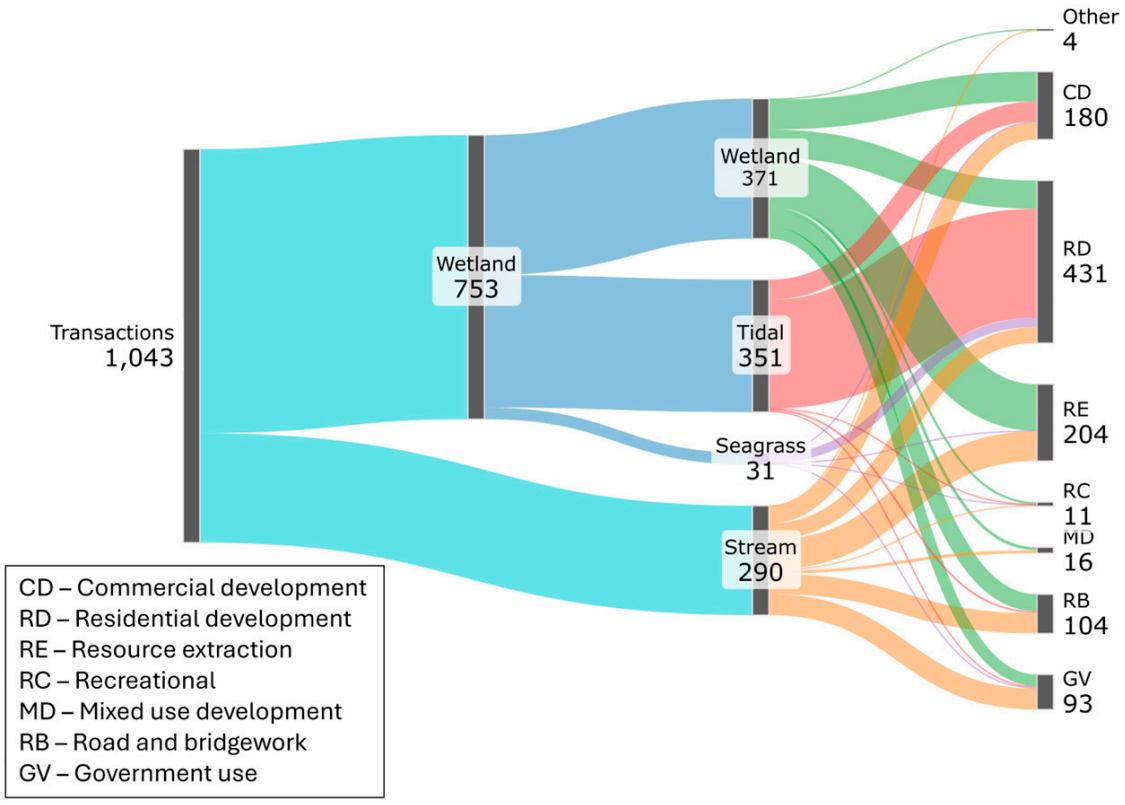

Figure 2. Sankey diagram illustrating the transaction flow from all assessed In-Lieu Fee (ILF) programs on public lands in the United States post-2008 (n = 1043 transactions). The flow is categorized by ecosystems (e.g., wetlands, streams) and impact types (e.g., mixed-use development), showing total number of transactions in each category.

3.2. Credit Proportions per Transaction

The analysis of credit allocations within ILF programs showed variability across both ecosystem types and credit categories (Table A1). Wetland and stream ecosystems had the highest mean proportions of credit allocations, at 1.09% (95% CI: 0.45% to 1.73%) and 1.38% (95% CI: 1.07% to 1.70%), respectively. Wetland credits, however, showed the greatest variability (SD = 6.21%), while stream credits exhibited more moderate variability (SD = 2.73%). Within ILF wetland credit allocations, variability tends to reflect the diversity of wetland subcategories, their broader spatial distribution, and the wide range of human–wetland interactions. In contrast, seagrass and tidal ecosystems had lower mean proportions of 0.0853% (95% CI: 0.03% to 0.13%) and 0.274% (95% CI: 0.22% to 0.32%), with seagrass exhibiting low variability (SD = 0.145%). The model further shows that ecosystem type plays a significant role in credit allocation. Wetland credits were allocated at significantly higher proportions relative to the stream ecosystem reference category (Estimate = 0.927, p-value = 0.0088). This indicates that, on a per-transaction basis, impacts to wetlands tend to be compensated with a larger proportion of an ILF program's available credits than impacts to streams. On the other hand, seagrass and tidal credits showed negative relationships with credit allocation (Seagrass Estimate = −0.829, p-value = 0.0248; Tidal Estimate = −0.627, p-value = 0.0732), with the latter being marginally significant. This indicates

that higher amounts of ILF credits are allocated toward stream ecosystems compared to seagrass and tidal ecosystems.

The model results indicate that the study focus, GV credits, did not receive significantly more or significantly less proportional transactions than CD credits (Estimate = 0.082, p-value = 0.341), with a mean proportion of 0.96% (CI 0.61; 1.32). RE credits received larger proportional transactions than CD credits, with a positive and statistically significant relationship (Estimate = 0.406, p-value = 0.00011). This is reflected in the data, where RE credits had the highest mean proportion at 1.89%, though with considerable variability (SD = 8.41%) and a confidence interval ranging from 0.73% to 3.05%. RE programs are typically larger in scale and often linked to impacts that are offset through credits dedicated primarily to those activities, resulting in higher proportional allocations to RE credits. In contrast, RD credits exhibited a negative relationship with credit allocation (Estimate = −1.001, p-value = 0.00029), showing the smallest mean proportion at just 0.343%, with a standard deviation of 0.578% and a CI between 0.29% and 0.40%. These results imply that fee programs tied to RDs tend to distribute credits more broadly across multiple impact types within a service area, which explains why RD credits appeared in smaller proportions. This could reflect the fact that RD projects often involve diverse, smaller-scale impacts that require offsetting through a wider mix of credit types.

Other credit types, such as MD and RB credits, showed more moderate effects in the model. MD credits had a positive but non-significant effect (Estimate = 0.127, p-value = 0.2288), while RB credits exhibited a borderline significant positive effect (Estimate = 0.336, p-value = 0.0716). Correspondingly, MD credits had a mean proportion of 1.38%, with moderate variation (SD = 2.30%) and a CI from 0.25% to 2.51%, while RB credits had a mean proportion of 1.28%, with an SD of 1.68% and a CI between 0.95% and 1.60%.

The credit allocation patterns emphasize that the type of impact being compensated for plays a significant role in determining the proportion of credits allocated within ILF programs. RE credits were allocated in the highest proportions, followed by RB and MD credits, while RD credits represented a smaller share based on their overall designated impact, overall fee program designation, and impacts offset in said program and service area. These trends are consistent with the model's results, which suggest that credit type and the associated impact are central factors influencing ILF credit allocations. The random effect for the program (variance = 1.15) highlights considerable variation across individual ILF programs. The model's Conditional R^2 of 0.625 indicates that 62.5% of the variance is explained by the fixed and random effects, with ecosystem types being the most significant factor in credit allocation (p-value = 3.034×10^{-16}).

3.3. Co-Occurrence Within Service Areas

In this context, network connectivity indicates which impact categories or ecosystem types serve as central nodes by linking to many others, while clustering highlights groups of impacts and ecosystems that commonly co-occur within service areas. Network credit transactions, focusing on strong relationships within service areas, were most often linked to wetland ecosystems (n = 58), followed by streams (n = 55), seagrass (n = 2), tidal (n = 2), non-tidal (n = 1), and subaqueous (n = 1; Figure 3a; Table A2). Impact categories within service areas were most associated with RE (n = 53), CD (n = 32), RB (n = 30), GV (n = 28), and RD (n = 25; Figure 3a). Network connectivity, expressed as the number of direct links each element has (degree centrality), was highest for RB and GV, which were linked to eleven other nodes in the network. CD and RD followed closely, each connected to ten nodes, while RC was less connected, with eight links. Among ecosystem types, seagrass, tidal, and non-tidal systems stood out as the most connected, each linking to seven different credit types. This pattern suggests that RB and GV credits, along with seagrass, tidal, and

non-tidal systems, function as key hubs in the network, indicating their significant role in linking diverse credit types and ecosystems within fee programs.

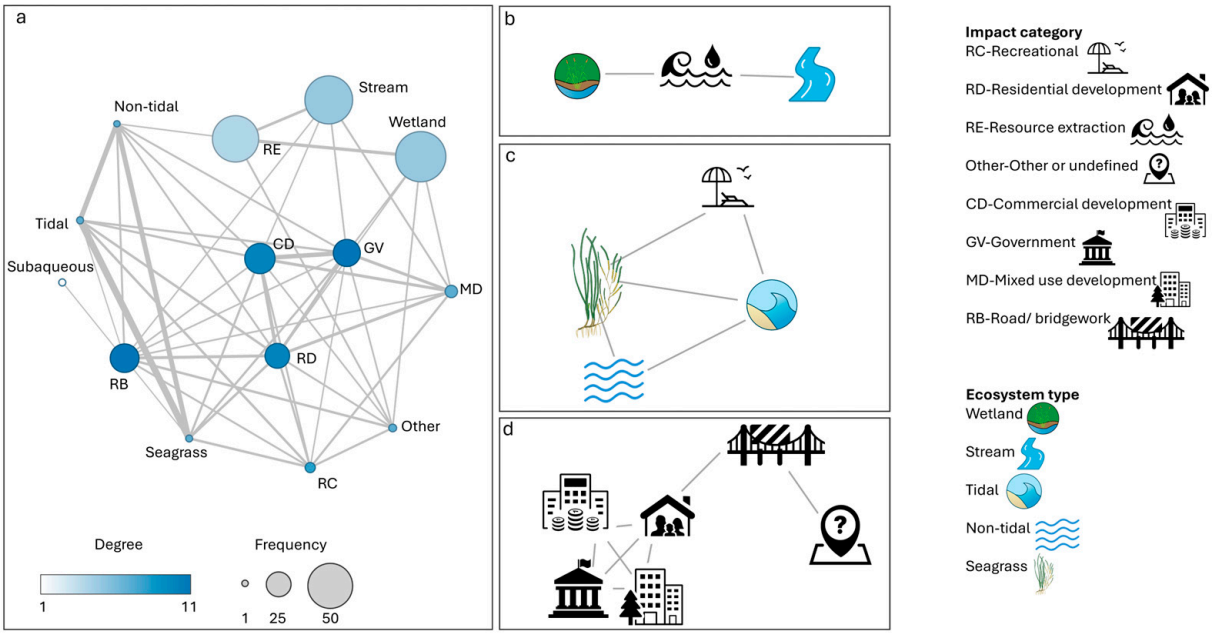

Figure 3. (**a**) Constrained network (p(Z) < 0.5; n = 305) showing connections between impact categories and ecosystem types from post-2008 U.S. ILF transactions. Node connectedness reflects transaction frequency and degree centrality; edge strength is based on p(Z) [45]. (**b**–**d**) Clusters highlight strongest connections (lowest third of *p*-values). Symbols: Jane Hawkey, Joanna Woerner, Kim Kraeer, Lucy Van Essen-Fishman, Tracey Saxby (Integration and Application Network); Dieter Tracey (Marine Botany UQ); ian.umces.edu/media-library (accessed on 12 July 2025); other symbols from uxwing.com (accessed on 14 July 2025).

Key relationships in the network clusters (Figure 3b–d; Table A3) include a strong connection within service areas between RE and both stream ($p < 0.01$) and wetland ecosystems ($p < 0.001$) (Cluster 1; Figure 3b), suggesting that resource extraction and related projects make up the most common impact on both streams and wetlands within service areas. Cluster 2 (Figure 3c) linked tidal, non-tidal and seagrass ecosystems with each other ($p < 0.001$), as well as tidal and seagrass to recreational impacts ($p = 0.01$; RC), indicating that recreational impacts within service areas tend to affect multiple coastal ecosystem types at the same time. Cluster 3 linked the different development types of CD, GV, RD and MD with each other ($p < 0.01$; Figure 3d). Residential developments within the same service areas were also linked to road and bridgework (RB; $p < 0.01$), and RB to other unspecified impacts ($p = 0.02$).

Overall, the network results indicate that development activities RB, GV, CD and RD play central roles on a service area scale within the constrained network, acting as key nodes. Resource extraction had a low degree of centrality but was the most common impact on wetlands and streams within service areas for residential and commercial development projects, as well as road and bridge construction tending to be linked together within services areas, whereas tidal and non-tidal ecosystem impacts tend to be of a recreational nature within service areas.

4. Discussion

The implementation of the 2008 Compensatory Mitigation Rule fundamentally reshaped the landscape of environmental mitigation in the United States, establishing a more

rigorous, standardized, and ecologically ambitious framework [51]. This rule created equivalent standards for all mitigation types and established a clear preference for third-party options like mitigation banks and ILF programs over traditional permittee-responsible mitigation [26,51,52]. Within this modernized regulatory context, this study's findings offer insights into how ILF programs function in practice, particularly in offsetting impacts on public lands [19]. The results indicate that these programs are not primarily responding to public infrastructure projects, but rather to the cumulative pressures of private development, and that their operational structure is uniquely suited to the complex challenges of contemporary land use patterns [19,26,51].

4.1. Private Development as the Primary Driver of ILF Transactions

Contrary to the initial expectation that government activities would be the main driver of mitigation needs, this study's findings show that private residential development, commercial projects, and resource extraction are the dominant sources of impacts requiring offsets on public lands. This finding reframes the narrative around environmental pressures on public lands, suggesting that policy and management could look beyond the impacts of public infrastructure and more critically address the potentially significant, cumulative effects of private enterprise and expansion. The legal trigger for these transactions is Section 404 of the Clean Water Act (CWA), which aims "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters" [53,54]. The permitting process follows the sequential mitigation hierarchy [6]. Only after avoidance, minimization, and rehabilitation steps are exhausted can compensatory mitigation be considered for the residual damage [6,51,55]. The prevalence of ILF transactions driven by the private sector underscores that this regulatory process is being applied more frequently to private development, often with smaller overall impacts, than to public works. While government projects and roadwork certainly contribute to ILF transactions, their roles appear to be secondary to the broader patterns of land use change driven by housing, commercial, and resource demands [56–58]. This pattern also intersects with ongoing debates about land use policy, particularly around zoning, suburban sprawl, and growth management. The prevalence of ILF transactions linked to private residential and commercial expansion highlights how land use decisions, such as permissive zoning for housing developments or the expansion of suburban and exurban areas, can indirectly shape mitigation demands on public lands [59–61]. Linking compensatory mitigation patterns to these broader policy debates suggests that offsetting is not just a matter of project-by-project regulation but also a reflection of cumulative choices in land use planning [60,61].

4.2. The Role of ILFs in Mitigating Development Impacts

The data show that wetland ecosystems are the primary focus of ILF transactions, which reflects the policy origins of compensatory mitigation in the U.S. under the Clean Water Act [53,54]. This prioritization is especially significant for public lands, which often contain large, ecologically vital wetland systems threatened by adjacent private development. In this context, ILFs act as a critical mechanism for land management agencies to channel mitigation funds toward these high-priority ecosystems [23,53].

Furthermore, the prevalence of residential development credits, which are often allocated in smaller proportional amounts, suggests that ILFs serve a unique niche by offsetting small-scale impacts, such as the construction of private docks or minor construction near waterways. These activities, while minor individually, contribute to cumulative ecosystem degradation [62,63]. For private landowners or small-scale developers, undertaking permittee-responsible mitigation (PRM) is often infeasible due to a lack of ecological expertise and the high costs associated with long-term monitoring and management [63,64].

Indeed, the often-high failure rate of PRM projects was a primary motivation for the 2008 Rule's preference for third-party providers [26,51,65]. The results show how ILF programs in that sense provide an essential tool by allowing permittees to transfer their mitigation liability to a qualified government or non-profit sponsor. By pooling fees from these smaller impacts, the ILF sponsor can fund larger, more ecologically meaningful, and professionally managed restoration projects [23,51,54]. This consolidation of financial and technical resources into larger, more resilient sites is a key advantage identified by regulators and a central goal of the 2008 Rule [23,27,66]. This highlights the program's flexibility in addressing a wide spectrum of impact scales on public lands, from minor residential encroachments to major commercial developments.

4.3. Interdependencies

One of the strongest findings is the high degree of interconnectedness among different impact types within service areas. The network analysis showed strong links between residential, commercial, mixed-use, and government projects, suggesting that these developments do not occur in isolation but as part of larger, interdependent growth patterns. This pattern underscores the challenge of addressing cumulative impacts in land use planning. An ILF program, by design, is exceptionally well-positioned to manage these aggregated impacts. A foundational principle of the 2008 Rule is the mandatory use of a "watershed approach" in selecting and designing mitigation projects [51]. This represented a strategic departure from the previous preference for on-site, in-kind replacement, which often resulted in small, disconnected, and ecologically non-viable fragmented wetlands [67,68]. The watershed approach requires that mitigation be planned strategically to address the most pressing needs of the entire watershed, such as improving water quality, restoring habitat connectivity, or addressing known sources of impairment [51,67,68]. By pooling funds from varied but related development projects across a service area, an ILF sponsor can implement a single, large-scale, strategic restoration project that is far more ecologically effective than multiple, small, disconnected permittee-responsible sites could ever be. This approach aligns with broader land use planning goals that seek to manage the total effect of development on a landscape rather than just the impact of individual projects [1,69–71]. At the same time, implementing a watershed-scale approach often faces hurdles, including jurisdictional fragmentation across municipalities, limited coordination among agencies, and funding constraints that can slow or constrain effective project delivery [72].

4.4. Actionable Recommendations

Based on the discussed findings, there are two concrete actionable recommendations that could enhance the effectiveness of ILF programs on public lands. Firstly, the previously mentioned and mandated watershed approach could be strengthened through more integrated mitigation plans at the service area level. Given the strong dependencies between residential, commercial, and government impacts, public land managers could collaborate more with ILF sponsors to develop more in-depth strategic plans that anticipate cumulative effects [9,73,74]. This recommendation builds directly upon the Compensation Planning Framework that the 2008 Rule requires ILF programs to establish [51]. This framework must use a watershed approach to identify ecological priorities and outline a strategy for site selection. By enhancing these frameworks with predictive models based on the observed development patterns, sponsors and regulators can proactively identify and prioritize large-scale restoration sites capable of offsetting impacts from multiple, interconnected development types, thereby maximizing the ecological return on investment and more effectively addressing cumulative impacts [9,12,75,76].

Secondly, long-term management and investment can be supported by data-driven credit forecasting and pricing. ILF programs could be enhanced through the implementation of more sophisticated, data-driven credit forecasting and pricing. This involves moving beyond traditional area-based requirements toward a more holistic valuation of impacted ecosystems [77–80]. ILF programs could increasingly use empirical data on impact types and on the interconnected nature of impacts, resulting in more accurately forecasted credit demand [23,35]. Furthermore, pricing models could be expanded to incorporate a wider array of the ecosystem services lost, such as water purification, flood storage, and critical habitat functions. While many compensatory mitigation systems still focus on area and ecological indicators, recent scientific assessment approaches are moving toward evaluations based on the comprehensive ecological, social, and economic values of these services, often captured through essential variables, covering ecological, social and economic dimensions [81–84]. Adopting such a comprehensive valuation method is essential for complying with the 2008 Rule's mandate for "full-cost accounting" and robust financial assurances [51]. Accurate, data-driven pricing ensures that the fees collected are sufficient to cover all project costs, including the often-underestimated expenses of land acquisition, design, perpetual monitoring, management, and legal defense of the site [26,85]. This would secure the long-term financial health of the program and its capacity to fund the comprehensive stewardship required for successful and permanent ecological restoration. Yet, the adoption of more complex valuation models raises questions of feasibility. Many agencies currently operate with limited technical capacity and funding, and valuation approaches that integrate ecological, social, and economic variables demand robust datasets, interdisciplinary expertise, and institutional coordination that may not always be available [69,72,86]. These gaps highlight the need for phased implementation, methodological standardization, and capacity building, if such models are to be applied effectively in practice.

5. Conclusions

This study highlights how ILF programs have evolved under the 2008 Compensatory Mitigation Rule to address complex and often cumulative development pressures on public lands. Contrary to expectations that government infrastructure would dominate, the analysis shows that private activities, residential expansion, commercial growth, and resource extraction are now the primary drivers of impacts requiring mitigation. Recognizing the weight of these private sector impacts shifts the emphasis of mitigation policy and land management, underscoring the need to anticipate and respond to diffuse, incremental sources of ecological change. Because these pressures increasingly originate from private sector growth rather than public works, ILF programs must be understood not only as a regulatory tool but as a key mechanism for channeling private development's fragmented impacts into coordinated ecological restoration. ILF programs demonstrate value by pooling contributions from numerous smaller permits and directing them into larger, strategically planned projects. This capacity not only addresses the limitations of permittee-responsible mitigation but also enables restoration efforts that align with broader watershed objectives. In doing so, ILFs help to safeguard ecologically significant systems, especially wetlands, which are central to the resilience of public lands facing adjacent development. The analysis further shows that development impacts are closely interlinked, creating cumulative challenges that cannot be effectively managed in isolation. ILF programs, with their watershed-scale orientation, are positioned to integrate these pressures and convert them into opportunities for coordinated, landscape-level restoration. Building on these insights, two areas of policy refinement are suggested, as follows: stronger integration of predictive planning within service areas to address cumulative effects, and more advanced

credit valuation systems that reflect the full ecological and economic costs of restoration. Together, these steps would enhance the long-term effectiveness and sustainability of ILF programs, ensuring they continue to deliver ecologically meaningful outcomes in the face of evolving land use demands.

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Appendix A

Appendix A.1

Table A1. Summary of the mixed-effects model results and associated diagnostic metrics. The table includes fixed effect estimates with standard errors, z-values, and *p*-values for predictors (including habitat types and credit categories), random effect variance components for ILF program, dispersion metrics, R^2 values, and Type III Wald chi-square tests. Additional sections provide insights into multicollinearity diagnostics (VIF and tolerance) and descriptive statistics for scaled proportional credit transactions within ILFs across different ecosystems and impact categories. Subaqueous and unspecific transactions are not included in the analysis due to small sample size (<5). * Indicate levels of significance; * $p < 0.05$; ** $p < 0.001$, *** $p < 0.0001$).

	Estimate	**Std Error**	**z-Value**	**Pr(>|z|)**
Intercept	−4.591	0.481	−9.538	$<2 \times 10^{-16}$
RE	0.406	−0.105	3.856	0.000115 ***
GV	0.082	0.086	0.951	0.341557
MD	0.127	0.105	1.203	0.228842
RB	0.336	0.186	1.801	0.071643
RC	−0.010	0.098	−0.106	0.915681
RD	−1.001	−0.276	−3.617	0.000299 ***
Wetland	0.927	0.354	2.619	0.008812 **
Seagrass	−0.829	0.369	−2.244	0.024846 *
Tidal	−0.627	0.350	−1.791	0.073290
Random effect	**Variance**	**Std. dev**		
Program	1.15	1.072		
Overdispersion		**Uniformity of residuals**		**Outlier test**
dispersion	*p*-value	D	*p*-value	*p*-value
1.223	0.280	0.0928	0.098	0.377
Conditional R^2	**Marginal R^2**			
0.625	0.221			

Analysis of Deviance Table (Type III Wald chi-square tests)

	chisq	**Df**	**Pr(>chisq)**
Intercept	116.385	1	$<2.2 \times 10^{-16}$
Impact	11.037	6	0.08726
Ecosystem	78.862	4	3.034×10^{-16} ***

Table A1. *Cont.*

	Estimate	Std Error	z-Value	Pr(>|z|)	
Multicollinearity	**VIF**	**VIF 95% CI**	**SE**	**Tolerance**	**Tolerance 95%**
Impact	1.14	[1.08, 1.25]	1.07	0.87	[0.80, 0.92]
Ecosystem	1.14	[1.08, 1.25]	1.07	0.87	[0.80, 0.92]
Low correlation					
	Mean %	**Median %**	**SD**	**CI lower**	**CI upper**
Stream	1.38	0.526	2.73	1.07	1.70
Seagrass	0.0853	0.0449	0.145	0.0343	0.136
Tidal	0.274	0.0632	0.498	0.222	0.327
Wetland	1.09	0.228	6.21	0.451	1.73
	Mean %	**Median %**	**SD**	**CI lower**	**CI upper**
RE	1.89	0.266	8.41	0.732	3.05
CD	0.639	0.219	2.42	0.285	0.993
GV	0.967	0.293	1.71	0.617	1.32
MD	1.38	0.478	2.30	0.249	2.51
RB	1.28	0.674	1.68	0.951	1.60
RC	0.659	0.608	0.650	0.275	1.04
RD	0.343	0.103	0.578	0.289	0.398

Appendix A.2

Table A2. Network characteristics between impact type categories and ecosystem types as part of ILF transactions (n = 1043) on public lands in the United States. Constrained network includes connection strengths p(Z) < 0.5 (n = 305). Table includes node frequency and degree centrality (connectivity within the network). Impact categories include government use (GV), resource extraction (RE), mixed development (MD), commercial development (CD), residential development (RD), road and bridgework (RB), and recreational (RC).

Name	Frequency	Degree (Centrality)
Impact category		
RB	30	11
CD	32	10
RC	6	8
RD	25	10
MD	9	7
RE	53	4
Other	3	7
GV	28	11
Ecosystem type		
Wetland	58	5
Non-tidal	1	7
Seagrass	2	7
Tidal	2	7
Subaqueous	1	1
Stream	55	5

Appendix A.3

Table A3. Network characteristics between impact type categories and ecosystem types as part of ILF transactions (n = 1043) on public lands in the United States. Constrained network includes connection strengths p(Z) < 0.5 (n = 305). Table includes link connection strength between nodes, Source-node to Target-node (Haberman; p(Z)). Impact categories include government use (GV), resource extraction (RE), mixed development (MD), commercial development (CD), residential development (RD), road and bridgework (RB), and recreational (RC). * Indicate levels of significance; * $p < 0.05$; ** $p < 0.001$, *** $p < 0.0001$).

Source	Target	Haberman	p(Z)
Seagrass	Tidal	8.72	2.32×10^{-13} ***
Non-tidal	Seagrass	6.12	1.87×10^{-8} ***
Non-tidal	Tidal	6.12	1.87×10^{-8} ***
CD	GV	5.4	3.68×10^{-7} ***
CD	RD	3.7	2.06×10^{-4} ***
RE	Wetland	3.26	8.31×10^{-4} ***
RB	RD	3.06	1.52×10^{-3} **
RD	MD	3.05	1.56×10^{-3} **
CD	MD	3.03	1.68×10^{-3} **
RD	GV	2.93	2.24×10^{-3} **
MD	GV	2.71	4.14×10^{-3} **
RE	Stream	2.59	5.70×10^{-3} **
RC	Seagrass	2.24	0.01 *
RC	Tidal	2.24	0.01 *
RB	Other	2.19	0.02 *
RD	Seagrass	2.05	0.02 *
RD	Tidal	2.05	0.02 *
GV	Seagrass	1.88	0.03 *
GV	Tidal	1.88	0.03 *
RC	RD	1.83	0.04 *
CD	Seagrass	1.68	0.05 *
CD	Tidal	1.68	0.05 *
RC	MD	1.7	0.05 *
RC	Other	1.67	0.05 *
RB	RC	1.42	0.08
RD	Non-tidal	1.44	0.08
CD	RC	1.27	0.1
RD	Other	1.27	0.1
GV	Non-tidal	1.32	0.1
RB	Non-tidal	1.25	0.11
RB	Subaqueous	1.25	0.11
CD	Non-tidal	1.18	0.12
MD	Stream	1.18	0.12
RE	Other	1.16	0.12
RB	CD	1.13	0.13
Other	GV	1.09	0.14
RB	MD	1.05	0.15
Other	Wetland	0.98	0.16
RB	GV	0.95	0.17
MD	Wetland	0.94	0.17
GV	Wetland	0.91	0.18
GV	Stream	0.92	0.18
CD	Other	0.88	0.19
RC	GV	0.7	0.24

Table A3. *Cont.*

Source	Target	Haberman	p(Z)
RB	Stream	0.68	0.25
RE	Non-tidal	0.66	0.25
RD	Wetland	0.53	0.3
CD	Stream	0.44	0.33
RB	Seagrass	0.31	0.38
RB	Tidal	0.31	0.38

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