**Title:** Global Change Asymmetrically Rewires Ecosystems

**Running Title:** Asymmetric Rewiring

**Authors:** Charlotte A. Ward1,2\*, Tyler D. Tunney2,1, Ian Donohue3, Carling Bieg4, Kayla R.S. Hale1, Bailey C. McMeans5, John C. Moore6, Kevin S. McCann1

**Affiliations:**

1University of Guelph; Guelph, Canada

2Fisheries and Oceans Canada; Moncton, Canada

3Trinity College Dublin; Dublin, Ireland

4Case Western Reserve University, Cleveland, USA

5University of Toronto Mississauga; Mississauga, Canada

6Colorado State University; Fort Collins, USA

\*Corresponding author. Address: 50 Stone Road East, Guelph, ON Canada, N1G 2W1;

Email: [cward@uoguelph.ca](mailto:cward@uoguelph.ca)

**Keywords**: Global change, food web, asymmetry, rewiring, ecosystem function, resilience, habitat coupling

**Article Information:**

Article Type: Synthesis

Abstract Word Count: 179

Main Text Word Count: 4635

Number of References: 85

Number of Tables: 1

Number of Figures: 4

Number of Text Boxes: 0

**Author Contributions**: All authors contributed to conceptualization. CAW, TDT, KSM, and ID developed the methodology. CAW led the investigation and supervision was provided by KSM and TDT. Visualization was conducted by CAW, CB, and KRSH. CAW wrote the original draft, and all authors contributed substantially to review and editing.

**Data Accessibility Statement:** All code for replicating the theoretical analyses (Julia script) and data visualizations (R script), along with a literature table summarizing the studies reviewed in this article, are available at: <https://github.com/charlotteamw/Asymmetric_Rewiring.git>. A public Zenodo repository for all final code and data will be uploaded before the manuscript is published.

**Abstract**

Global change is altering ecosystems in ways that threaten the critical functions on which biodiversity depends. Despite this, we know very little about how drivers of global change broadly affect food webs. While an industry of studies documents shifts in whole carbon pathways within food webs in response to anthropogenic pressures, a comprehensive synthesis is lacking. To address this, we provide empirical examples across diverse ecosystems and conduct a systematic literature review to reveal the prevalence of asymmetric rewiring – a phenomenon whereby drivers of global change consistently but disproportionally alter the flow of some carbon pathways relative to others. Further, using food web models, we show how asymmetric rewiring erodes resilience and disrupts key functions, such as primary and secondary production. Global change is complex and multidimensional, making it challenging to understand how human activities affect ecosystem processes. Our work critically synthesizes empirical evidence to uncover a remarkably general response in food webs to global environmental change that needs to be better understood to protect nature and the services that human societies rely on in a rapidly changing world.

**Introduction**

Asymmetry - the disproportion in the spatial arrangement of sides or parts of an entity - is a ubiquitous property of nature from molecular to planetary scales (Knoblich, 2010; Neumüller & Knoblich, 2009; Rathore et al., 2020). Widely recognized examples of asymmetries include the right-hand twist of the double helix of DNA (Watson & Crick, 1953), the migrating eye of flatfish (Campinho et al., 2018), the enlarged claw of a male fiddler crab (Morgan, 1923), left or right handedness in humans (Amunts et al., 1996), and differences in air temperature between the northern and southern hemisphere (Feulner et al., 2013). Recently, asymmetry has also been recognized as an important component of heterogeneity shaping the spatial arrangement of food webs (Rooney et al., 2006) – the web of life that feeds biodiversity. In these complex food webs, spatially adjacent habitats, such as benthic and pelagic zones in aquatic systems, differ in productivity and rates of energy transfer, and the balance in carbon flows between habitats is a key driver of the function and resilience of the overall system (Allen-Perkins et al., 2023; McCann & Rooney, 2009; Schindler & Scheuerell, 2002).

At the same time ecologists have begun to characterize the effects of asymmetry on food web stability (Allen-Perkins et al., 2023; Rooney et al., 2006), they are grappling with a critical threat to biodiversity and ecosystems. The activities of eight billion people on the planet are generating novel pressures through a suite of human-driven global changes (e.g., climate change, land conversion, biological invasions, nutrient application to agricultural systems, and pollution; Millennium Ecosystem Assessment, 2005; Nelson et al., 2006). Indeed, recent work has introduced the idea that climate change impacts different habitats asymmetrically (Bartley et al., 2019; Blanchard, 2015). Mobile consumer species then respond to these changes by shifting their habitat use (e.g., for foraging). These habitat changes and concomitant consumer responses ultimately alter the spatial structure of food webs and lead to the ‘rewiring’ of the topological patterning and strength of food web linkages (Bartley et al., 2019; Blanchard, 2015). In principle, however, this rewiring could arise from any form of anthropogenic pressure, whether acting at the scale of microhabitats or spanning entire ecosystems, yet this possibility has not been comprehensively explored. Consequently, it is imperative that we better understand novel sources of rewiring in response to global environmental change – hereafter termed asymmetric rewiring (Table 1) – to protect nature and the ecological services that human societies rely on.

An emerging argument for how anthropogenic pressures asymmetrically rewire food webs involves the reconfiguring of the spatial and temporal compartmentalization of ecosystems (Krause et al., 2003; Stouffer & Bascompte, 2011). Food webs are structured around distinct habitats characterized by specific physical and abiotic conditions that support different assemblages of basal resources and primary consumers. Many upper trophic level species are highly mobile (i.e., mobile generalist consumers; Table 1; Stiling et al., 2023), traversing habitat boundaries to source energy and resources across a diverse landscape (McCann et al., 2005; Rooney et al., 2008). This mobility allows mobile generalist consumers to rapidly respond to changes in environmental conditions through their behaviour, such that they can avoid habitats with less available resources or that impose negative physiological consequences (McCann & Rooney, 2009). However, the exposure of mobile generalist consumers to differential anthropogenic pressures as they integrate energy and resources among distinct habitat types is also a mechanism for asymmetric rewiring. Anthropogenic pressures may result in such extreme habitat asymmetries that some habitats become inhospitable due to novel physical and biological properties (Tunney et al., 2014). This can result in reduced energy transfer and restrict options for consumers in a variable world, thereby eroding productivity and resilience. A perspective that encompasses how human-driven global change rewires food webs more generally is, however, lacking. Such a perspective is required to provide timely scientific advice to those charged with managing nature in the face of global change.

To address this gap, we adopt a synthetic approach to present an emerging perspective for asymmetric rewiring of food webs under global change. First, we elucidate the conceptual arguments for asymmetric rewiring, revisiting, and building on previous work positing that anthropogenic pressures are broadly impacting habitats and ecosystems asymmetrically, creating novel heterogeneity across spatial scales. We argue that this heterogeneity results in the rewiring of the organization of food webs, and present three examples highlighting the prevalence and ecological significance of this phenomenon. We then systematically review the habitat coupling (see Table 1 for definition) literature to explore the universality of asymmetric rewiring and assay change in whole carbon spatial pathways through higher-order, generalist, mobile consumers across a wide array of terrestrial and aquatic ecosystems. We conduct simulations using models that emulate patterns that emerged from the literature review to assess the potential impacts of rewiring on food web structure, ecosystem functions, and resilience. The simulations reveal that the rewiring of food web structure may erode the resilience of ecosystems and key functions, such as species biomass production. We conclude by highlighting future directions to leverage this understanding for management strategies aimed at enhancing and protecting ecosystem resilience and functions in an era of rapid global environmental change.

**The Recipe for Asymmetric Rewiring**

Asymmetric rewiring depends on two key ingredients. First, asymmetric rewiring is driven by the inherent spatial compartmentation of food webs (Krause et al., 2003; Moore & Hunt, 1988). Lower trophic level organisms tend to occupy discrete habitats whereas upper trophic level organisms, such as mobile generalist consumers (see Table 1 for definition), forage across habitat boundaries (Fig.1; Keppeler et al., 2021; Rooney et al., 2008). This creates a nested structure of habitat coupling (Table 1) across space and trophic levels (Vander Zanden & Vadeboncoeur, 2002). Notably, while habitat coupling can occur at various trophic levels (Stiling et al., 2023), mobile generalist consumers at higher trophic levels play a crucial role by integrating large areas and adapting their habitat use in response to environmental changes (Kortsch et al., 2019; Law & Dickman, 1998; Tunney et al., 2014). Thus, the ability of mobile generalist consumers to withstand a range of environmental conditions, coupled with differences in the productivity of prey in different habitats, determine the availability and consumption of resources (Marklund et al., 2018; Ward et al., 1998). This consumption sets up the blend of strong and weak interactions between consumers and resources from different habitats (Rooney et al., 2006).

Second, impacts from anthropogenic pressures are unlikely to exhibit a perfectly symmetrical spatial signature across all scales, leading to differential impacts across spatially distinct habitats or ecosystems (Fig. 1). Even spatially general phenomena, such as climate warming, yield varied impacts as they interact with different habitat or ecosystem matrices, which filter anthropogenic pressures differentially (Rathore et al., 2020; Xu & Ramanathan, 2012). For example, warming surface waters in a thermally stratified lake affects shallow waters more strongly than cooler deep waters (Pilla et al., 2020). Similarly, invasive species tend to have more or less impact on different habitats based on their habitat preferences (Hecky & Hesslein, 1995).

Given this, mobile generalist consumers readily respond to changes in the environmental conditions or resource availability among the habitats that they couple across (Fig. 1). The asymmetric impacts of anthropogenic pressures alter consumers’ access to more heavily impacted habitats and/or change the density of resources within these habitats, reshaping their foraging behaviours and position within the broader food web. The consequent asymmetric rewiring potentially involves changes in food web topology (topological rewiring; Table 1), interaction strengths (interaction strength rewiring; Table 1), and the traits or vital rates of the species that form nodes within the food web (e.g., survival and reproduction; Cosset et al., 2019; Srinivasan et al., 2015; node rewiring; Table 1).

Under this definition, asymmetric rewiring can manifest in various ways. However, a key manifestation is the alteration of the spatial structure of food webs as mobile generalist consumers that feed among different habitats adjust their degree of habitat coupling (Schindler & Scheuerell, 2002). This leads us to argue that asymmetric impacts due to drivers of global change reorganize food webs by altering distinct carbon pathways (Table 1) from basal resources to upper trophic levels, and is reflected in the behaviour (e.g., habitat use for foraging) of mobile generalist consumer species. As such, empirical estimates of altered habitat coupling among mobile generalist consumers (e.g., the fate of basal carbon) act as assays to document whole food web changes and, thus, the extent of asymmetric rewiring (Alp & Cucherousset, 2022).

**Empirical Observations of Asymmetric Rewiring**

We now turn to empirical examples to highlight the diversity of asymmetric rewiring responses across ecosystems globally. We discuss three cases where the spatial structure of food webs has been significantly altered due to a variety of anthropogenic pressures that impact habitats (micro- or macrohabitats) asymmetrically and therefore the spatial habitat use and foraging behaviour of a mobile generalist consumer. Each of these ecosystems have experienced changes in food web structure with substantiative consequences for their biodiversity and resilience. After examining these specific instances of asymmetric rewiring, we then illustrate how these transformations are not isolated events, but rather reflect a broad pattern of global ecological change, by presenting a systematic review of the literature on generalist consumer habitat coupling.

*Examples of asymmetric rewiring*

*From fungal to bacterial pathways in agro-ecosystems.* Agriculture is vital for supporting the burgeoning demands of human population growth. Nevertheless, ecosystems are undergoing significant transformations due to the expansion of commercial farming (Neyret et al., 2024). This expansion has drastically impacted below-ground food webs (i.e., soil ecosystems), which are responsible for sequestering approximately 2500 gigatons of carbon globally (Lal, 2004). In these systems, the soil matrix comprises distinct microhabitat compartments characterized by wet and dry pore spaces (Moore & Hunt, 1988). Typically, the interactions between fungal organisms, which are associated with dry pore spaces, and soil predators are weaker than those involving bacterial organisms, which are associated with wet pore spaces. This difference in interaction strengths is attributed to the temporal dynamics of the different food web compartments (Moore et al., 1993; Moore & DeRuiter, 1991; Rooney et al., 2006). However, agricultural practices that employ intensive tillage and irrigation homogenize the soil matrix, favoring the establishment of wet pore space and dramatically reducing the availability of dry pore space (Fig. 2b; asymmetric impact depicted by the loss of the ‘blue’ dry pore space microhabitat compartment). This shift often leads predatory soil organisms to alter their foraging by relying more on the increasingly productive wet/bacterial energy pathway (Moore & Mueller, 2024). Theoretical and empirical analyses suggest that the resilience of these food webs is compromised under intensive agriculture regimes since the ability of soil predators to adaptively forage on temporally asynchronous resources is diminished (Moore, 1994; Rooney et al., 2008). Additionally, the reduced density of organisms associated with the dry/fungal energy pathway is likely to impact soil carbon sequestration and nutrient cycling—vital functions of soil ecosystems that are expected to play a major role in buffering the effects of climate change (Amelung et al., 2020).

*Shift from offshore to nearshore production in the Laurentian Great Lakes.* The Laurentian Great Lakes contain almost one-fifth of the world's supply of freshwater (Thomas et al., 2017), support 179 fish species, and provide several other ecosystem services to the approximately 34 million people living in the basin (Michigan Sea Grant, 2024). Due to their size and utilization by humans, there have been a number of highly publicized species invasions (Griffiths et al., 1991; Kornis et al., 2013). In particular, the invasion of dreissenid mussels (*Dreissena polymorpha* and *Dreissena bugensis*) is having a significant negative impact on offshore habitats within Great Lakes by redirecting nutrients and energy away from pelagic primary production and into the nearshore zones they inhabit (Hecky et al., 2011; Fig. 2c; asymmetric impact depicted by the loss of the ‘blue’ pelagic habitat compartment). This has caused lake whitefish (*Coregonus clupeaformis*), a cold-water profundal consumer, to alter its diet and increasingly rely on nearshore energy sources since the introduction of dreissenid mussels in the late 1980s (Fera et al., 2017; Rennie et al., 2009). Concomitantly, whitefish populations have experienced dramatic declines and reduced body condition (Pothoven et al., 2001), which has been attributed to their preference for the colder, more oxygenated offshore habitats that have become increasingly desolate and resource poor with the establishment of dreissenids (Johannsson et al., 2000). Along with these changes, the resilience of food webs in the Great Lakes has diminished, evidenced by the extinction of several pelagic species including *C. johannae, C. alpenae, and C. kiyi orientalis*, largely due to overfishing, the impact of invasive species, and habitat degradation (Bunnell et al., 2023).

*From ice to open waters in the Arctic.* Eastern Greenland encompasses a unique Arctic ecosystem that is heavily impacted by ongoing climate change. Loss of sea-ice in the region is occurring at an alarming rate of 9.8% per decade (Perovich & Richter-Menge, 2009), which has drastically reduced seasonally available ice-associated habitats (Laidre et al., 2015), and simultaneously increased the size and accessibility of pelagic open water habitats (Fig. 2a; asymmetric impact depicted by the loss of the ‘blue’ ice-associated habitat compartment). This change in ice cover has significantly altered polar bears’ ability to access their preferred prey. In response to the asymmetric impacts of climate change on Arctic habitats, polar bears have been documented over the past 30 years consuming significantly less ice-associated prey, such as ringed seals, and more sub-Arctic pelagic prey, such as hooded seals (McKinney et al., 2013). Recent experimental and observational research suggests that the dietary shift of Eastern Greenland polar bears toward sub-arctic pelagic species—which are known to contain substantially higher concentrations of persistent organic pollutants (POPs) than ice-dependent arctic seals—may be detrimental to their reproductive success and immune systems due to increased levels of POPs and mercury exposure (Letcher et al., 2010; Sonne, 2010). Thus, climate warming is threatening the persistence of an important predator species through changes in its reproduction and survival (Stirling & Derocher, 2012), and therefore the resilience of this Arctic ecosystem as a whole (Rezende et al., 2021).

*Emerging patterns of habitat coupling under global change*

We review the literature to identify emerging patterns of habitat coupling to better understand the systemic impacts of anthropogenic pressures across various ecological settings. Despite the apparent utility of habitat coupling as a measure of food web structure under global change (Bartels et al., 2016; Codron et al., 2012), the literature on the rewiring of habitat coupling by mobile generalist consumers has not been synthesized. To address this gap, we conducted a structured literature search and vote count analysis of peer-reviewed studies that use stable isotope analysis to document generalist consumer habitat coupling responses to anthropogenic pressures linked to global change. Stable isotope approaches offer a relatively straightforward and rapid way to characterize changes in habitat coupling by tracing material from isotopically distinct basal resources to upper trophic levels, thereby assessing asymmetric impacts through the behaviour of generalist consumers (Alp & Cucherousset, 2022).

Anthropogenic pressures were categorized as altering habitat coupling in ways that increased, decreased, or did not change the reliance of higher order generalist consumer species (e.g., secondary consumers and predators) on resources from multiple habitats or food web compartments. We also categorized studies by habitat type and the mechanisms driving changes in habitat coupling where any were provided. After extensively searching and screening the literature (433 primary research articles), we validated a set of 57 studies (detailed approach described in Supplementary Materials S1). We use this novel dataset to (1) test the idea that human drivers of global change affect habitat coupling by generalist consumers, and (2) to characterize whether and why these drivers have similar or divergent effects on habitat coupling.

We found that 81% of the studies identified by our search detected a response in habitat coupling to the asymmetric impacts of anthropogenic pressures (46 out of 57 studies; Fig. 3a; Table S1). Approximately 59% of those (27 out of 46 studies, 48% of all studies examined) indicated a decrease in habitat coupling, meaning that a generalist consumer responded to anthropogenic pressure by increasing their intake of resources from one dominant habitat and decreased their reliance on resources from additional habitats. An increase in habitat coupling toward a more equitable reliance on multiple habitat compartments was reported in 33% of studies (19 of 57 studies), while no change in coupling in response to drivers of global change was found in 19% of studies in our review (11 out of 57 studies). Studies that focused on anthropogenic pressures associated with climate change were most numerous (*n* = 14), followed by land conversion (*n* = 12), and biological invasions (*n* = 10; Fig. 3b; Table S1). Climate change most often led to increases in habitat coupling (*n* = 8; 57% of studies examining this driver of global change), whereas land conversion tended to result in a decoupling of habitats (*n* = 8; 67% of studies examining this driver of global change). Biological invasions showed a tendency to decrease habitat coupling by consumers (*n* = 5; 50% of studies examining this driver of global change), but also had a significant proportion of no change results (*n* = 3; 30% of studies examining this driver of global change).

Our literature review revealed that the habitat coupling literature is dominated by studies of aquatic ecosystems, comprising the focus of 76% (43 out of 57) of studies included in our analysis. Studies of lentic ecosystems (e.g., lakes) were most prevalent (*n* = 21) followed by marine ecosystems (*n* = 11) and lotic ecosystems (e.g., rivers; *n* = 10). Furthermore, we identified two common mechanisms that influence the availability of prey resources to consumers, namely the density of resources and their accessibility. Changes in habitat coupling due to altered resource density occur when the productivity (primary or secondary) of distinct habitats is affected by anthropogenic pressures (Hunt et al., 2020). Whereas changes in habitat coupling due to accessibility occur when the fraction of resource density within habitats that a consumer can acquire becomes limited due to anthropogenic pressures. This limitation can arise, for example, when environmental conditions within a habitat become so physiologically stressful that a consumer avoids foraging in that habitat (Tunney et al., 2012). We found that resource density is a more broadly identified mechanistic driver of change in habitat coupling in the literature compared to changes in the accessibility of prey in a particular habitat (67% and 12% of studies that reported a change in habitat coupling, respectively), but that both increases and decreases in consumer habitat coupling were identified in both categories (Fig. 3c).

The asymmetric rewiring of food webs from global change is ubiquitous and complex. The directional responses of rewiring vary but, in general, habitat coupling among generalist consumers is changing with clear patterns for important anthropogenic pressures and ecosystem types. This empirical evidence supports the conceptual framework depicted in Fig. 1 and demonstrates how the spatial compartmentation of food webs and mobile consumer behaviour underpin general patterns in the responses of ecosystems to drivers of global change.

**Rewiring is Restructuring and Refunctioning Ecosystems**

We have shown that anthropogenic pressures associated with global change are broadly restructuring food webs through the process of asymmetric rewiring. This is concerning, because central to ecological theory is the understanding that the structure of ecosystems profoundly influences their processes (Pauly et al., 1998; Petchey et al., 1999; Sackett et al., 2010). Thus, global change is not only rewiring (restructuring) ecosystems but also, critically, refunctioning them. To explore the mechanisms underlying this structure-function-dynamic relationship in the context of global change, we first refer to the processes driving rewiring (as depicted in Fig. 1 and identified in our review of the habitat coupling literature).

The compartmentalized carbon pathways depicted in Fig. 1 form the structural response framework to changing habitat conditions. Importantly, this framework has been well studied in the theoretical stability literature (McCann et al., 2005; Moore & William Hunt, 1988). Here, we draw from a simple model example that recreates the gradient in responses to changing habitat conditions as a conceptual entry point to how asymmetric rewiring is simultaneously changing key structures, functions, and dynamic properties (i.e., resilience, Fig. 4; Table 1). In what follows, the resilience result is qualitatively general regardless of the mechanisms that drive asymmetry across different habitats. That is, the greatest dynamical stability (i.e., smallest maximum real eigenvalue), occurs at intermediate values of habitat coupling strength and the greatest instability occurs at either perfect symmetry or a single food chain (Fig. 4b.v; see Supplementary Materials S1 for parameter values; Rooney & McCann, 2012). It is also important to note that the ways in which food web structure changes in response to anthropogenic pressures depend on the assumptions of the mechanism that drives asymmetric rewiring. In particular, the degree of habitat coupling may increase or decrease depending on how each habitat is affected by a particular anthropogenic pressure. For example, here, we explore the effects of changing productivity within one habitat compartment.

Specifically, in this example, we assume that one habitat compartment is experiencing reductions in productivity (that is, the basal resource’s carrying capacity) while the other habitat is unimpacted (Fig. 4a; blue circles represent trophospecies in Habitat 1; yellow circles represent trophospecies in Habitat 2). By decreasing primary productivity in one habitat compartment (through decreasing its carrying capacity), we are also decreasing the potential prey density in that habitat, echoing the main mechanistic driver of changing habitat coupling in our literature review. The result is a combination of structural changes over this gradient (e.g., reduced habitat coupling [Fig. 4b. i], and increased predator (P) to trophospecies C1 ratio [Fig. 4b. ii]) that can be measured in a real system. Note, the inflated P:C1 ratio occurs because of the dwindling resource supply in Habitat 1 (i.e., C1 declines in the face of reduced productivity in Habitat 1).

Further, the changing functions in this case follow the assumed mechanism (i.e., reduced productivity in Habitat 1 under global change), yielding reduced total primary production (Fig. 4b. iii) and reduced top predator secondary production (the loss of a whole carbon pathway reduces the predator’s production; Fig. 4b. iv). In response to asymmetric rewiring, resilience (i.e., equilibrium [maximum real eigenvalues] and non-equilibrium [predator co-efficient of variation] measures of dynamic stability) follows the hump-shaped result that is well known (see Supplementary Materials S1 for further detail; Rooney et al., 2006). Specifically, resilience peaks at intermediate levels of habitat coupling where predators can respond to variation in prey densities (i.e., consumer trophospecies) in the different habitats following a small perturbation (Fig. 4b. v) or to stochastically perturbed dynamics (Fig. 4b. vi; Gellner & McCann, 2016; Rooney et al., 2006) in ways that support more stable predator populations (i.e., higher mean density and smaller magnitude of population cycles) and thus reduce the likelihood of predator population collapse in a stochastic world (i.e., reduced CV).

This example highlights the important relationships between food web structure, ecosystem function, and dynamics (i.e., resilience). Further, and importantly, these findings underscore the utility of key food web structures (e.g., habitat coupling) as an indicator for monitoring ecosystem functions and resilience in the face of global change, reinforcing the necessity to integrate these insights into broader ecological management and conservation strategies.

**Conclusions**

The asymmetric rewiring of food webs is a widespread consequence of global change. Our literature review evaluating the impacts of anthropogenic pressures on food webs revealed that whole carbon pathways are becoming asymmetrically rewired across ecosystems globally. This phenomenon occurs because mobile generalist consumers alter their reliance on energy derived from distinct habitats in the presence of anthropogenic pressure. In cases where anthropogenic pressures are highly asymmetric and render some habitats inhospitable or depleted of resources, mobile generalist consumers that acquire resources from multiple habitats may ultimately lose access to entire carbon pathways, leading to adverse effects on their secondary production, and per theory, the resilience of whole food webs (McCann et al., 2005). Such a loss removes key 'switch points' that mobile generalist consumer species use to flexibly adapt their behaviour in response to natural and human-induced perturbations (McMeans et al., 2016). We note that these global change and food web asymmetries likely appear across scales (e.g., soil microhabitats (Moore, 1994) to entire hemispheres (Imrit & Sharma, 2021)) suggesting that eroding these stabilizing processes concurrently may yield deleterious effects for organisms across trophic levels, affecting ecosystems in profound and potentially irreversible ways.

Based on our literature review, diverse responses in consumer habitat coupling occur across all anthropogenic pressures and ecosystem types. Climate change tended to increase consumer habitat coupling, which may arise due to decreased access to a preferred prey (Tunney et al., 2014) or increased production in a previously unproductive habitat (Wang et al., 2016; as in Fig. 2c). The conversion of naturally complex habitats to more simplified ecosystems is consistent with land conversion tending to decrease habitat coupling in our review(as in Fig. 2a). Invasion tended to decrease habitat coupling and may reflect instances when prolific invasive species shift production to a single dominant energy pathway (Gobel et al., 2023; Wood et al., 2017; as in Fig. 2b). Importantly, asymmetric rewiring may temporarily increase food web symmetry by increasing or decreasing the degree of consumer habitat coupling toward an intermediate proportion where habitats are equally coupled in response to anthropogenic pressures (as it has in 33% of the studies examined here). However, because anthropogenic change is sustained, and directional, increased symmetry is a transitional state as the dominance shifts from one habitat to another. Eventually, the asymmetric impacts of anthropogenic pressures are likely to result in the loss or near-loss of entire food web pathways in the most affected habitats.

Our synthesis of asymmetric rewiring provides a conceptual framework to link human activities and associated changes in the properties of ecosystems. Changes in ecosystem function and resilience are expected to depend on the mechanisms driving novel asymmetries in the structure of food webs. For example, a food web cut off from one productive carbon pathway, yet experiencing an overall increase in productivity (e.g., streams experiencing increased nutrient runoff after riparian removal; Champagne et al., 2022), will be affected differently than a food web where the total productivity decreases following the loss of a carbon pathway (e.g., lake trout losing access to nearshore areas due to warming (Tunney et al., 2014)). Understanding and identifying the mechanisms driving asymmetric rewiring is vital for leveraging this perspective in policy and management operations during an era of rapid global change. Integrated monitoring programs that follow the fate of asymmetrical impacts can aid in identifying changes in habitat conditions (e.g., using sensors to detect abiotic or biotic conditions) and energy flow throughout food webs (e.g., using stable isotope analysis), and thus delineate mechanisms of asymmetric rewiring. Collectively, such monitoring systems promise the potential for a suite of early warning signals of looming change, including alterations to the spatial structure of food webs, which can be employed in the mitigation and restoration of global ecosystems. To this end, resource managers are developing strategies to adapt to global change that use frameworks and tools that are amenable to integrating the concept of asymmetric rewiring (Antwi et al., 2024; Boyce et al., 2021; Schindler & Hilborn, 2015). For example, considering the spatial scale and intensity of human pressures on habitats may prove critical for ecosystem approaches to managing harvest or prioritizing habitat for protection or restoration. The use of single-species management tactics could also benefit from this broader perspective. Strategies might include considering how mobile generalist consumers shape spatial food web structures when planning for species redistribution—whether through managing habitat for connectivity to facilitate animal dispersal, or human-facilitated translocations—to enhance resilience in vulnerable populations. By embracing this perspective on asymmetric rewiring, we can better safeguard the resilience and functions of ecosystems in a changing world.

**References**

Allen-Perkins, A., García-Callejas, D., Bartomeus, I., & Godoy, O. (2023). Structural asymmetry in biotic interactions as a tool to understand and predict ecological persistence. *Ecology Letters*, *26*(10), 1647–1662. https://doi.org/https://doi.org/10.1111/ele.14291

Alp, M., & Cucherousset, J. (2022). Food webs speak of human impact: Using stable isotope-based tools to measure ecological consequences of environmental change. *Food Webs*, *30*, e00218. https://doi.org/https://doi.org/10.1016/j.fooweb.2021.e00218

Amelung, W., Bossio, D., de Vries, W., Kögel-Knabner, I., Lehmann, J., Amundson, R., Bol, R., Collins, C., Lal, R., Leifeld, J., Minasny, B., Pan, G., Paustian, K., Rumpel, C., Sanderman, J., van Groenigen, J. W., Mooney, S., van Wesemael, B., Wander, M., & Chabbi, A. (2020). Towards a global-scale soil climate mitigation strategy. *Nature Communications*, *11*(1), 5427. https://doi.org/10.1038/s41467-020-18887-7

Amunts, K., Schlaug, G., Schleicher, A., Steinmetz, H., Dabringhaus, A., Roland, P. E., & Zilles, K. (1996). Asymmetry in the Human Motor Cortex and Handedness. *NeuroImage*, *4*(3), 216–222. https://doi.org/https://doi.org/10.1006/nimg.1996.0073

Antwi, E. K., Burkhardt, H., Boakye-Danquah, J., Doucet, T., & Abolina, E. (2024). Review of climate change adaptation and mitigation implementation in Canada’s forest ecosystems part I: Reporting, science, and institutional/governance supporting practices in Canada. *Environmental Reviews*, *32*(1), 16–41. https://doi.org/10.1139/ER-2022-0130/ASSET/IMAGES/ER-2022-0130\_TAB12.GIF

Bartels, P., Hirsch, P. E., Svanback, R., & Eklov, P. (2016). Dissolved Organic Carbon Reduces Habitat Coupling by Top Predators in Lake Ecosystems. *Ecosystems*, *19*(6), 955–967. https://doi.org/10.1007/s10021-016-9978-x

Bartley, T. J., McCann, K. S., Bieg, C., Cazelles, K., Granados, M., Guzzo, M. M., MacDougall, A. S., Tunney, T. D., & McMeans, B. C. (2019). Food web rewiring in a changing world. *Nature Ecology & Evolution 2019 3:3*, *3*(3), 345–354. https://doi.org/10.1038/S41559-018-0772-3

Blanchard, J. L. (2015). A rewired food web. *Nature*, *527*(7577), 173–174. https://doi.org/10.1038/nature16311

Boyce, D. G., Fuller, S., Karbowski, C., Schleit, K., & Worm, B. (2021). Leading or lagging: How well are climate change considerations being incorporated into canadian fisheries management? *Canadian Journal of Fisheries and Aquatic Sciences*, *78*(8), 1120–1129. https://doi.org/10.1139/CJFAS-2020-0394/SUPPL\_FILE/CJFAS-2020-0394SUPPL.PDF

Bunnell, D. B., Ackiss, A. S., Alofs, K. M., Brant, C. O., Bronte, C. R., Claramunt, R. M., Dettmers, J. M., Honsey, A. E., Mandrak, N. E., Muir, A. M., Santucci, V. J., Smith, D. R., Strach, R. M., Sweka, J. A., Weidel, B. C., Mattes, W. P., & Newman, K. R. (2023). A science and management partnership to restore coregonine diversity to the Laurentian Great Lakes. *Environmental Reviews*, *31*(4), 716–738. https://doi.org/10.1139/ER-2022-0109/ASSET/IMAGES/ER-2022-0109\_F3.JPG

Campinho, M. A., Silva, N., Martins, G. G., Anjos, L., Florindo, C., Roman-Padilla, J., Garcia-Cegarra, A., Louro, B., Manchado, M., & Power, D. M. (2018). A thyroid hormone regulated asymmetric responsive centre is correlated with eye migration during flatfish metamorphosis. *Scientific Reports*, *8*(1), 12267. https://doi.org/10.1038/s41598-018-29957-8

Champagne, E. J., Guzzo, M. M., Gutgesell, M. K., & McCann, K. S. (2022). Riparian buffers maintain aquatic trophic structure in agricultural landscapes. *Biology Letters*, *18*(3). https://doi.org/10.1098/rsbl.2021.0598

Codron, J., Codron, D., Sponheimer, M., Kirkman, K., Duffy, K. J., Raubenheimer, E. J., Mélice, J. L., Grant, R., Clauss, M., & Lee-Thorp, J. A. (2012). Stable isotope series from elephant ivory reveal lifetime histories of a true dietary generalist. *Proceedings of the Royal Society B: Biological Sciences*, *279*(1737), 2433–2441. https://doi.org/10.1098/RSPB.2011.2472

Cosset, C. C. P., Gilroy, J. J., & Edwards, D. P. (2019). Impacts of tropical forest disturbance on species vital rates. *Conservation Biology*, *33*(1), 66–75. https://doi.org/10.1111/COBI.13182

Dolson, R., McCann, K., Rooney, N., & Ridgway, M. (2009). Lake morphometry predicts the degree of habitat coupling by a mobile predator. *OIKOS*, *118*(8), 1230–1238. https://doi.org/10.1111/j.1600-0706.2009.17351.x

Donohue, I., Hillebrand, H., Montoya, J. M., Petchey, O. L., Pimm, S. L., Fowler, M. S., Healy, K., Jackson, A. L., Lurgi, M., McClean, D., O’Connor, N. E., O’Gorman, E. J., & Yang, Q. (2016). Navigating the complexity of ecological stability. *Ecology Letters*, *19*(9), 1172–1185. https://doi.org/https://doi.org/10.1111/ele.12648

Fera, S. A., Rennie, M. D., & Dunlop, E. S. (2017). Broad shifts in the resource use of a commercially harvested fish following the invasion of dreissenid mussels. *Ecology*, *98*(6), 1681–1692. https://doi.org/https://doi.org/10.1002/ecy.1836

Feulner, G., Rahmstorf, S., Levermann, A., & Volkwardt, S. (2013). On the origin of the surface air temperature difference between the hemispheres in earth’s present-day climate. *Journal of Climate*, *26*(18), 7136–7150. https://doi.org/10.1175/JCLI-D-12-00636.1

Folke, C. (2016). Resilience (republished). *Ecology and Society*, *21*(4).

Gellner, G., & McCann, K. S. (2016). Consistent role of weak and strong interactions in high- and low-diversity trophic food webs. *Nature Communications*, *7*. https://doi.org/10.1038/ncomms11180

Gobel, N., Laufer, G., González-Bergonzoni, I., Soutullo, Á., & Arim, M. (2023). Invariant and vulnerable food web components after bullfrog invasion. *Biological Invasions*, *25*(3), 901–916. https://doi.org/10.1007/S10530-022-02956-7/FIGURES/5

Griffiths, R. W., Schloesser, D. W., Leach, J. H., & Kovalak, W. P. (1991). Distribution and Dispersal of the Zebra Mussel (Dreissena polymorpha) in the Great Lakes Region. *Canadian Journal of Fisheries and Aquatic Sciences*, *48*(8), 1381–1388. https://doi.org/10.1139/f91-165

Hecky, R. E., & Hesslein, R. H. (1995). Contributions of benthic algae to lake food webs as revealed by stable isotope analysis. *Journal of the North American Benthological Society*, *14*(4), 631–653. https://doi.org/10.2307/1467546

Hecky, R. E., Smith, R. E. H., Barton, D. R., Guildford, S. J., Taylor, W. D., Charlton, M. N., & Howell, T. (2011). The nearshore phosphorus shunt: a consequence of ecosystem engineering by dreissenids in the Laurentian Great Lakes. *Canadian Journal of Fisheries and Aquatic Sciences, 61*(7), 1285–1293. https://doi.org/10.1139/F04-065

Hunt, J. L., Paterson, H., Close, P., & Pettit, N. E. (2020). Riparian condition influences spider community structure and the contribution of aquatic carbon subsidies to terrestrial habitats. *Science of The Total Environment*, *746*, 141109. https://doi.org/10.1016/J.SCITOTENV.2020.141109

Imrit, M. A., & Sharma, S. (2021). Climate Change is Contributing to Faster Rates of Lake Ice Loss in Lakes Around the Northern Hemisphere. *Journal of Geophysical Research: Biogeosciences*, *126*(7), 1–13. https://doi.org/10.1029/2020JG006134

Johannsson, O. E., Dermott, R., Graham, D. M., Dahl, J. A., Millard, E. S., Myles, D. D., & LeBlanc, J. (2000). Benthic and Pelagic Secondary Production in Lake Erie after the Invasion of Dreissena spp. with Implications for Fish Production. *Journal of Great Lakes Research*, *26*(1), 31–54. https://doi.org/10.1016/S0380-1330(00)70671-X

Keppeler, F. W., Olin, J. A., López-Duarte, P. C., Polito, M. J., Hooper-Bùi, L. M., Taylor, S. S., Rabalais, N. N., Fodrie, F. J., Roberts, B. J., Turner, R. E., Martin, C. W., & Jensen, O. P. (2021). Body size, trophic position, and the coupling of different energy pathways across a saltmarsh landscape. *Limnology and Oceanography Letters*, *6*(6), 360–368. https://doi.org/https://doi.org/10.1002/lol2.10212

Knoblich, J. A. (2010). Asymmetric cell division: Recent developments and their implications for tumour biology. *Nature Reviews Molecular Cell Biology, 11*(12)*,* 849-860. https://doi.org/10.1038/nrm3010

Kornis, M. S., Sharma, S., & Jake Vander Zanden, M. (2013). Invasion success and impact of an invasive fish, round goby, in Great Lakes tributaries. *Diversity and Distributions*, *19*(2), 184–198. https://doi.org/https://doi.org/10.1111/ddi.12001

Kortsch, S., Primicerio, R., Aschan, M., Lind, S., Dolgov, A. V, & Planque, B. (2019). Food‐web structure varies along environmental gradients in a high‐latitude marine ecosystem. *Ecography*, *42*(2), 295–308.

Krause, A. E., Frank, K. A., Mason, D. M., Ulanowicz, R. E., & Taylor, W. W. (2003). Compartments revealed in food-web structure. *Nature, 426*(6964), 282–285. https://doi.org/10.1038/nature02115

Laidre, K. L., Born, E. W., Heagerty, P., Wiig, Ø., Stern, H., Dietz, R., Aars, J., & Andersen, M. (2015). Shifts in female polar bear (Ursus maritimus) habitat use in East Greenland. *Polar Biology*, *38*(6), 879–893. https://doi.org/10.1007/s00300-015-1648-5

Lal, R. (2004). Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science*, *304*(5677), 1623–1627. https://doi.org/10.1126/science.1097396

Law, B. S., & Dickman, C. R. (1998). The use of habitat mosaics by terrestrial vertebrate fauna: implications for conservation and management. *Biodiversity & Conservation*, *7*, 323–333.

Letcher, R. J., Bustnes, J. O., Dietz, R., Jenssen, B. M., Jørgensen, E. H., Sonne, C., Verreault, J., Vijayan, M. M., & Gabrielsen, G. W. (2010). Exposure and effects assessment of persistent organohalogen contaminants in arctic wildlife and fish. *Science of The Total Environment*, *408*(15), 2995–3043. https://doi.org/10.1016/J.SCITOTENV.2009.10.038

Marklund, M. H. K., Svanbäck, R., Zha, Y., Scharnweber, K., & Eklöv, P. (2018). The influence of habitat accessibility on the dietary and morphological specialisation of an aquatic predator. *Oikos*, *127*(1), 160–169. https://doi.org/https://doi.org/10.1111/oik.04094

McCann, K. S., Rasmussen, J. B., & Umbanhowar, J. (2005). The dynamics of spatially coupled food webs. *Ecology Letters*, *8*(5), 513–523. https://doi.org/10.1111/J.1461-0248.2005.00742.X

McCann, K. S., & Rooney, N. (2009). The more food webs change, the more they stay the same. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1524), 1789–1801. https://doi.org/10.1098/RSTB.2008.0273

McKinney, M. A., Iverson, S. J., Fisk, A. T., Sonne, C., Rigét, F. F., Letcher, R. J., Arts, M. T., Born, E. W., Rosing-Asvid, A., & Dietz, R. (2013). Global change effects on the long-term feeding ecology and contaminant exposures of East Greenland polar bears. *Global Change Biology*, *19*(8), 2360–2372. https://doi.org/10.1111/GCB.12241

McMeans, B. C., McCann, K. S., Tunney, T. D., Fisk, A. T., Muir, A. M., Lester, N., Shuter, B., & Rooney, N. (2016). The adaptive capacity of lake food webs: From individuals to ecosystems. *Ecological Monographs*, *86*(1), 4–19. https://doi.org/10.1890/15-0288.1

Merriam-Webster. (2024, September 3). *definition of ASYMMETRY*. Merriam-Webster.Com.

Millennium Ecosystem Assessment (Program). (2005). *Ecosystems and human well-being: synthesis*. Island Press.

Moore, J. C. (1994). Impact of agricultural practices on soil food web structure – theory and application. *Agriculture Ecosystems & Environment,* *51*(1–2), 239–247. https://doi.org/10.1016/0167-8809(94)90047-7

Moore, J. C., & DeRuiter, P. C. (1991). Temporal and spatial heterogeneity of trophic interactions within belowground food webs. *Agriculture Ecosystems & Environment*, *34*(1–4), 371–397. https://doi.org/10.1016/0167-8809(91)90122-E

Moore, J. C., DeRuiter, P. C., & Hunt, H. W. (1993). Soil invertebrate/micro-invertebrate interactions: disproportionate effects of species on food web structure and function. *Veterinary Parasitology*, *48*(1–4), 247–260. https://doi.org/10.1016/0304-4017(93)90160-O

Moore, J. C., & Mueller, N. (2024). Chapter 17 - The application of knowledge in soil microbiology, ecology, and biochemistry (SMEB) to the solution of today’s and future societal needs. In E. A. Paul & S. D. Frey (Eds.), *Soil Microbiology, Ecology and Biochemistry (Fifth Edition)* (pp. 493–536). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-12-822941-5.00017-X

Moore, J. C., & William Hunt, H. (1988). Resource compartmentation and the stability of real ecosystems. *Nature*, *333*(6170), 261–263. https://doi.org/10.1038/333261a0

Morgan, T. H. (1923). The development of asymmetry in the fiddler crab. *The American Naturalist*, *57*(650), 269–273.

Nelson, G. C., Bennett, E., Berhe, A. A., Cassman, K., DeFries, R., Dietz, T., Dobermann, A., Dobson, A., Janetos, A., Levy, M., Marco, D., Nakicenovic, N., O’Neill, B., Norgaard, R., Petschel-Held, G., Ojima, D., Pingali, P., Watson, R., & Zurek, M. (2006). an Overview. *Ecology and Society*, *11*(2). http://www.jstor.org/stable/26266018

Neumüller, R. A., & Knoblich, J. A. (2009). Dividing cellular asymmetry: Asymmetric cell division and its implications for stem cells and cancer. In *Genes and Development*, *23*(23), 2675–2699. https://doi.org/10.1101/gad.1850809

Neyret, M., Le Provost, G., Boesing, A. L., Schneider, F. D., Baulechner, D., Bergmann, J., de Vries, F. T., Fiore-Donno, A. M., Geisen, S., Goldmann, K., Merges, A., Saifutdinov, R. A., Simons, N. K., Tobias, J. A., Zaitsev, A. S., Gossner, M. M., Jung, K., Kandeler, E., Krauss, J., … Manning, P. (2024). A slow-fast trait continuum at the whole community level in relation to land-use intensification. *Nature Communications 15*(1), 1–23. https://doi.org/10.1038/s41467-024-45113-5

Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., & Torres, F. (1998). Fishing down marine food webs. *Science*, *279*(5352), 860–863. https://doi.org/10.1126/SCIENCE.279.5352.860/ASSET/7CA6E4AA-F71A-4918-8552-3CF2B6121FDF/ASSETS/GRAPHIC/SE0686248005.JPEG

Perovich, D. K., & Richter-Menge, J. A. (2009). Loss of Sea Ice in the Arctic\*. *Annual Review of Marine Science*, *1*, 417–441. https://doi.org/https://doi.org/10.1146/annurev.marine.010908.163805

Petchey, O. L., McPhearson, P. T., Casey, T. M., & Morin, P. J. (1999). Environmental warming alters food-web structure and ecosystem function. *Nature*, *402*(6757), 69–72. https://doi.org/10.1038/47023

Pilla, R. M., Williamson, C. E., Adamovich, B. V, Adrian, R., Anneville, O., Chandra, S., Colom-Montero, W., Devlin, S. P., Dix, M. A., Dokulil, M. T., Gaiser, E. E., Girdner, S. F., Hambright, K. D., Hamilton, D. P., Havens, K., Hessen, D. O., Higgins, S. N., Huttula, T. H., Huuskonen, H., … Zadereev, E. (2020). Deeper waters are changing less consistently than surface waters in a global analysis of 102 lakes. *Scientific Reports*, *10*(1), 20514. https://doi.org/10.1038/s41598-020-76873-x

Pothoven, S. A., Nalepa, T. F., Schneeberger, P. J., & Brandt, S. B. (2001). Changes in Diet and Body Condition of Lake Whitefish in Southern Lake Michigan Associated with Changes in Benthos. *North American Journal of Fisheries Management*, *21*(4), 876–883.

Rathore, S., Bindoff, N. L., Phillips, H. E., & Feng, M. (2020). Recent hemispheric asymmetry in global ocean warming induced by climate change and internal variability. *Nature Communications,* *11*(1), 1–8. https://doi.org/10.1038/s41467-020-15754-3

Rennie, M. D., Sprules, W. G., & Johnson, T. B. (2009). Factors affecting the growth and condition of lake whitefish (Coregonus clupeaformis). *Canadian Journal of Fisheries and Aquatic Sciences*, *66*(12), 2096–2108. https://doi.org/10.1139/F09-139

Rezende, F., Antiqueira, P. A. P., Petchey, O. L., Velho, L. F. M., Rodrigues, L. C., & Romero, G. Q. (2021). Trophic downgrading decreases species asynchrony and community stability regardless of climate warming. *Ecology Letters*, *24*(12), 2660–2673. https://doi.org/10.1111/ELE.13885

Rooney, N., McCann, K., Gellner, G., & Moore, J. C. (2006). Structural asymmetry and the stability of diverse food webs. *Nature, 442*(7100), 265–269. https://doi.org/10.1038/NATURE04887

Rooney, N., & McCann, K. S. (2012). Integrating food web diversity, structure and stability. *Trends in Ecology & Evolution*, *27*(1), 40–46. https://doi.org/10.1016/J.TREE.2011.09.001

Rooney, N., McCann, K. S., & Moore, J. C. (2008). A landscape theory for food web architecture. *Ecology Letters*, *11*(8), 867–881. https://doi.org/10.1111/J.1461-0248.2008.01193.X

Sackett, T. E., Classen, T., Sanders, N. J., Sackett, T. E., Classen, A. T., & Sanders, N. J. (2010). Linking soil food web structure to above- and belowground ecosystem processes: a meta-analysis. *Oikos*, *119*(12), 1984–1992. https://doi.org/10.1111/J.1600-0706.2010.18728.X

Schindler, D. E., & Hilborn, R. (2015). Prediction, precaution, and policy under global change. *Science*, *347*(6225), 953–954. https://doi.org/10.1126/science.1261824

Schindler, D. E., & Scheuerell, M. D. (2002). Habitat coupling in lake ecosystems. *Oikos*, *98*(2), 177–189. https://doi.org/10.1034/j.1600-0706.2002.980201.x

Michigan Sea Grant (2024). *Michigan Sea Grant 2024-2027 Strategic Plan*.

Sonne, C. (2010). Health effects from long-range transported contaminants in Arctic top predators: An integrated review based on studies of polar bears and relevant model species. *Environment International*, *36*(5), 461–491. https://doi.org/10.1016/J.ENVINT.2010.03.002

Srinivasan, U., Hines, J. E., & Quader, S. (2015). Demographic superiority with increased logging in tropical understorey insectivorous birds. *Journal of Applied Ecology*, *52*(5), 1374–1380. https://doi.org/10.1111/1365-2664.12475

Steffen W, Sanderson A, Tyson P, Jäger J, Matson P, Moore B, Oldfield F, Richardson K, Schellnhuber HJ, Turner BL, Wasson RJ. (2005). *Global Change and the Earth System: A Planet Under Pressure*. Springer Berlin, Heidelberg.

Stiling, R. R., Olden, J. D., Bouletreau, S., Cucherousset, J., & Holtgrieve, G. W. (2023). Global investigation of lake habitat coupling by fishes. *Oecologia, 202,* 617–628*.* https://doi.org/10.1007/s00442-023-05424-8

Stirling, I., & Derocher, A. E. (2012). Effects of climate warming on polar bears: a review of the evidence. *Global Change Biology*, *18*(9), 2694–2706. https://doi.org/https://doi.org/10.1111/j.1365-2486.2012.02753.x

Stouffer, D. B., & Bascompte, J. (2011). Compartmentalization increases food-web persistence. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(9), 3648–3652.

Thomas, L. M., Jorgenson, Z. G., Brigham, M. E., Choy, S. J., Moore, J. N., Banda, J. A., Gefell, D. J., Minarik, T. A., & Schoenfuss, H. L. (2017). Contaminants of emerging concern in tributaries to the Laurentian Great Lakes: II. Biological consequences of exposure. *PLOS ONE*, *12*(9), e0184725. https://doi.org/10.1371/JOURNAL.PONE.0184725

Tunney, T. D., McCann, K. S., Lester, N. P., & Shuter, B. J. (2012). Food web expansion and contraction in response to changing environmental conditions. *Nature Communications, 3, 1105*. https://doi.org/10.1038/ncomms2098

Tunney, T. D., McCann, K. S., Lester, N. P., & Shuter, B. J. (2014). Effects of differential habitat warming on complex communities. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(22), 8077–8082. https://doi.org/10.1073/pnas.1319618111

Van Meerbeek, K., Jucker, T., & Svenning, J. C. (2021). Unifying the concepts of stability and resilience in ecology. *Journal of Ecology*, *109*(9), 3114–3132. https://doi.org/10.1111/1365-2745.13651

van Oevelen, D., Soetaert, K., Middelburg, J. J., Herman, P. M. J., Moodley, L., Hamels, I., Moens, T., & Heip, C. H. R. (2006). Carbon flows through a benthic food web: Integrating biomass, isotope and tracer data. *Journal of Marine Research*, *64*(3), 453–482. https://doi.org/10.1357/002224006778189581

Wang, S. W., Springer, A. M., Budge, S. M., Horstmann, L., Quakenbush, L. T., & Wooller, M. J. (2016). Carbon sources and trophic relationships of ice seals during recent environmental shifts in the Bering Sea. *Ecological Applications*, *26*(3), 830–845. https://doi.org/10.1890/14-2421

Ward, C. A., Tunney, T. D., & McCann, K. S. (2023). Managing aquatic habitat structure for resilient trophic interactions. *Ecological Applications*, *33*(3), e2814. https://doi.org/https://doi.org/10.1002/eap.2814

Ward, J. P., Gutiérrez, R. J., & Noon, B. R. (1998). Habitat Selection by Northern Spotted Owls: The Consequences of Prey Selection and Distribution. *The Condor*, *100*(1), 79–92. https://doi.org/10.2307/1369899

Watson, J. D., & Crick F. H. C. (1953). Molecular Structure of Nucleic Acids: A Structure for Deoxyribose Nucleic Acid. *Nature*, *171*(4356), 737–738. https://doi.org/10.1038/171737a0

Wood, K. A., Hayes, R. B., England, J., & Grey, J. (2017). Invasive crayfish impacts on native fish diet and growth vary with fish life stage. *Aquatic Sciences*, *79*(1), 113–125. https://doi.org/10.1007/S00027-016-0483-2/FIGURES/5

Xu, Y., & Ramanathan, V. (2012). Latitudinally asymmetric response of global surface temperature: Implications for regional climate change. *Geophysical Research Letters*, *39*(13), 13706. https://doi.org/10.1029/2012GL052116

Vander Zanden, M. J., & Vadeboncoeur, Y. (2002). Fishes as Integrators of Benthic and Pelagic Food Webs in Lakes. *Ecology*, *83*(8), 2152. https://doi.org/10.2307/3072047

**Table 1.** Definitions of key terms and concepts related to the asymmetric rewiring of food webs under global change.

|  |  |
| --- | --- |
| **Term** | **Definition** |
| Asymmetry | The disproportion in the spatial arrangement of sides or parts of an entity (Merriam-Webster, 2024). |
| Global change | Broad-scale changes to the Earth's environment caused by human activities, impacting climate, ecosystems and their processes, and biodiversity (Steffen et al., 2005). |
| Anthropogenic pressure | Human activities that alter natural environments, such as land conversion, fossil fuel burning, species harvesting, intensive agriculture, and the spread of invasive species (Van Meerbeek et al., 2021). |
| Mobile generalist consumer | Organisms, typically at higher trophic levels (e.g., secondary consumers and predators), that move and forage across multiple habitat types and rely on a variety of food sources (McCann et al., 2005). |
| Habitat coupling | The dependence of a consumer on resources from spatially distinct habitats, effectively linking otherwise discrete food web compartments (Dolson et al., 2009; McMeans et al., 2016). |
| Carbon pathway | A sequence of spatially compartmented trophic interactions within a food web, where carbon flows from primary producers (e.g., algae and detritus) through intermediate trophic levels (e.g., herbivores and secondary consumers) to top predators (van Oevelen et al., 2006). |
| Asymmetric rewiring | A phenomenon where anthropogenic pressures unevenly impact different habitats, altering energy flow between basal resources and mobile generalist consumers to a greater extent in one habitat than another. Note that shifts in the foraging behaviour of consumers in response to these changes can result in a more or less symmetrical spatial food web structure depending on how habitats are affected and the initial reliance of mobile generalist consumers on resources from each habitat. |
| Interaction strength rewiring | A form of asymmetric rewiring that arises from changes in the strengths of interactions in a local food web (the magnitude of the effect on the energy flow from one species to another), which often result from changes in the consumptive demand of a consumer associated with changes in the consumer’s behaviour (Bartley et al., 2019). |
| Topological rewiring | A form of asymmetric rewiring that arises from changes in the topology of a local food web (who eats whom), which often result from novel species introductions and/or the loss of species. Note that topological rewiring is an extreme case of interaction strength rewiring, where an interaction is added or eliminated from the food web (Bartley et al., 2019; Blanchard, 2015). |
| Node rewiring | A form of asymmetric rewiring that arises from changes in the traits or vital rates of species within a food web (such as reproduction and survival; Cosset et al., 2019), which often occur due to shifts in environmental conditions or resource availability that ultimately affect population demographics. |
| Resilience | A measure of the persistence of systems and of their ability to absorb change and disturbance while maintaining their functions (Donohue et al., 2016; Folke, 2016). Here, resilience is calculated as the maximum real eigenvalue of the system (i.e., local stability), or as the co-efficient of variation (CV) of the system in a stochastic scenario (non-equilibrium stability) (Ward et al., 2023). |

**Figure Legends**

**Fig. 1.** The spatial compartmentation of food webs combined with the asymmetric impacts of anthropogenic pressures on different habitats drive asymmetric rewiring. In spatially compartmented food webs, lower trophic level organisms (blue and yellow circles) occupy distinct habitats (Habitat 1 and Habitat 2) while mobile generalist consumers at higher trophic levels (black circles) forage across habitat boundaries, linking otherwise discrete carbon pathways within food webs. As anthropogenic pressures—such as climate change, biological invasions, and land conversion—affect these habitats unevenly, they induce asymmetric impacts that lead to changes in consumer behaviour. These shifts alter the topology (presence of circles and black arrows), interaction strengths (width of black arrows), and the size and quality of the nodes (size of circles) within the food web. For simplicity, the figure shows a generalist mobile top predator coupling resources from two distinct habitats. As pressures intensify, predators adjust their foraging strategies, causing shifts in the spatial structure of the food web, resulting in asymmetric rewiring.

**Fig. 2.** Asymmetric impacts from anthropogenic pressures on habitats (blue and yellow compartments) alter carbon flows from basal resources to top predators. In all examples, the blue habitat represents the more impacted habitat, as resources within this habitat have become less available relative to resources in the yellow habitat. (A) Soil food webs in natural grasslands and intensive agricultural systems. Agricultural practices such as tillage and fertilizer input increase bacterial activity in the soil matrix, decreasing the relative reliance of predatory soil organisms (e.g., predatory nematodes) on the slower-cycling fungal pathway (Moore & Mueller, 2024). This shift reduces the C:N ratio of detritus and alters net primary productivity of plant communities, affecting soil carbon sequestration. (B) Laurentian Great Lakes food web before and after the invasion of dreissenid mussels. Dreissenid mussels divert pelagic primary production to nearshore benthic zones, leading lake whitefish to interact more with less-preferred nearshore resources (Fera et al., 2017), reducing body condition and population size in Lake Huron (Rennie et al., 2009). (C) Arctic food webs under historical (30 years ago) and modern sea-ice conditions. Longer ice-free seasons in Eastern Greenland have shifted polar bear diets away from ice-associated prey (e.g., ringed seals) to subarctic pelagic seals (e.g., hooded seals;McKinney et al., 2013), resulting in increased exposure to persistent organic pollutants (POPs) compared to 30 years ago, as subarctic seals carry higher levels of POPs than Arctic seals.

**Fig. 3.** Summary of responses of whole carbon pathways to anthropogenic pressures. (A) The percentage of studies (total n = 57) that found a generalist consumer species did not change (grey) or asymmetrically changed (black) their degree of habitat coupling via increases (light blue) or decreases (dark blue) in response to an anthropogenic pressure associated with global change. (B) The number of studies included in the analysis that investigate eachanthropogenic pressure and their results. (C) The mechanistic driver of these responses shown as changes in the accessibility of the consumers or density of resources in a particular habitat.

**Fig. 4.** Anthropogenic pressures rewire (restructure) and refunction ecosystems. (A) Our 5-trophospecies generalist food web module depicting a top predator (black circle) that couples prey from Habitat 1 (blue circles) and Habitat 2 (yellow circles) but has a slight preference for prey in Habitat 1. As anthropogenic pressure increases, the structure of the food web is rewired, shifting from a coupled two-compartment food web to an uncoupled 3-trophospecies food chain. (B) A theoretical experiment to examine the structure (i, ii), function (iii, iv), and dynamics (i.e., resilience) (v, vi) of our generalist food web module to asymmetric rewiring. (i) As asymmetric rewiring increases along the x-axis, the top predator (P) consumes less of trophospecies C1 (second trophic level; blue) and more of trophospecies C2 (second trophic level; yellow), and the predator’s degree of coupling is reduced. (ii) Simultaneously, the predator to consumerbiomass ratio (P:C1) increases exponentially in Habitat 1. Concomitant with these changes in structure, functions such as primary production (iii) and top predator production (iv) decrease, while (v) the equilibrium stability (maximum real eigenvalues) is unimodal. When we stochastically perturb this system, the top predator CV shows a similar response to the equilibrium stability by first decreasing (i.e., reduced population variation and increased non-equilibrium stability) and then increasing dramatically (i.e., increased population variation and decreased non-equilibrium stability).