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Climate Change-Driven Reorganization of Plant-Animal Interactions and Ecosystem Resilience: A Global Narrative

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Abstract

Climate change is reorganizing the ecological relationships that sustain terrestrial, freshwater, and coastal ecosystems. This global narrative evidence review examines how warming, changing precipitation, rising atmospheric CO_2, land-use transformation, fire, and associated disturbances alter plant-animal interactions through phenological shifts, spatial redistribution, physiological responses, and reorganization of interaction networks. The review synthesizes authoritative global indicators and peer-reviewed evidence on pollination, herbivory, seed dispersal, biodiversity, ecosystem carbon, and resilience. The updated NOAA Global Surface Temperature Data Set (NOAA Global Temp v6.1) indicates that the 2024 global mean land-ocean temperature anomaly was 1.42 °C above the 1850–1900 baseline, while the Mauna Loa annual mean CO_2 concentration reached 424.61 ppm. The 2024 Living Planet Index reported a 73% decline in average monitored vertebrate population abundance between 1970 and 2020. Phenological responses remain heterogeneous: reported advances are faster for temperate trees (5.2 days per decade) than for migratory birds (2.1 days per decade), creating potential temporal mismatches. In the European Alps, leading edge shifts were 17–40 m per decade for plants and 47–91 m per decade for animals, while historical

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isotherm velocity was 62–71 m per decade. Plant biodiversity decline is associated with scenario-dependent long-term vegetation-carbon-loss exposure of 7.44–103.14 Pg C under global sustainability (SSP1/RCP2.6) and 10.87–145.95 Pg C under fossil-fueled development (SSP5/RCP8.5); these are modeled exposure ranges, not observed losses. Overall, the evidence supports interaction-, trait-, and network-based environmental management, including phenological monitoring, habitat connectivity, native plant restoration, refutation, reducing non-climatic stressors, and integrated climate-biodiversity planning.

Introduction

The Earth system is undergoing simultaneous physical and biological reorganization. Atmospheric CO_2 exceeded 420 ppm in the 2020s, global temperature has risen by more than 1.4 °C relative to the pre-industrial period, and species are shifting their distributions [1, 2]. These changes propagate through ecological networks because plants and animals depend on one another for reproduction, food, movement, population regulation, and habitat modification [3–5]. Plant-animal relationships are particularly sensitive to climate change because interacting partners frequently respond at different rates. Warming may advance flowering, insect emergence, migration, or fruiting, while drought and habitat fragmentation can reduce the resources and spatial connectivity needed for interactions [6]. The resulting temporal and spatial mismatches can reduce reproductive success, alter food-web structure, weaken regeneration, and reduce ecosystem services [7–10]. Whether climate change leads to species loss is only part of the central ecological question; another is what will change in species interactions, how often they will occur, and whether replacement interactions will perform the same ecological functions as the interactions lost. The network may experience brief respite from disturbance, but disturbance can eventually reduce redundancy and make specialized interactions more vulnerable [11–14].

Ecosystem stability is multidimensional. Resistance describes the ability to remain near a previous state during disturbance, whereas resilience describes recovery after disturbance. Persistence and variability provide additional dimensions. Plant-animal networks add an important layer because the same number of species can support very different levels of functional connectivity. Networks can be represented as matrices in which plants and animals are nodes and visitation, pollen transfer, fruit removal, seed deposition, herbivory, or predation are links. Connectability, blessedness, modularity, specialization, robustness, and redundancy describe complementary aspects of network organization [12]. Phenology includes flowering, leaf-out, insect emergence, migration, nesting, fruiting, and other recurring biological events. Warming often advances spring phenology, but plants, insects, and migratory animals do not necessarily respond to the same cues. Different cue sensitivities can reduce temporal overlap between interacting partners. A plant may flower before a specialist pollinator emerges, or fruit may ripen after a principal disperser has moved away [6, 11]. Animal pollination links floral phenology and pollinator behavior to plant reproduction and agricultural production. Warming, extreme heat, drying, pesticide exposure, pathogens, habitat loss, light pollution, and declining floral resources can affect both partners. Specialist pollinators may be especially vulnerable because they have fewer alternative partners, whereas generalists may switch among plants; however, replacement visits do not necessarily deliver equivalent pollination effectiveness [6, 15].

Herbivores transfer plant biomass to consumers, regulate plant dominance, generate spatial heterogeneity, and influence nutrient cycling. Climate change can alter both herbivore activity and plant defense. Elevated CO_2 may reduce leaf nitrogen, drought may increase defensive compounds, and warming may accelerate insect development while simultaneously changing food quality [8]. Predator declines can release herbivore populations from top-down control, reduce tree regeneration, and alter vegetation structure, soil processes, and carbon storage [16,17]. Plant range shifts depend on dispersal, vegetative expansion, or assisted movement. Endocrinology, epizoochory, seed caching, and fruit removal are important dispersal pathways. Declines of large-bodied herbivores can restrict long-distance dispersal, gene flow, recruitment, and forest recovery, thereby limiting the ability of some plant populations to track shifting climates [7, 18]. Climate change rarely acts

alone. Habitat fragmentation can prevent movement, agricultural intensification can shorten floral resource calendars, urban heat islands can alter phenology, and changing fire regimes can restructure regeneration. Evidence indicates that habitat loss can amplify the effects of warming and altered precipitation, supporting integrated climate and land use management [9,19,20].

Accordingly, this review has five objectives: (1) to compile and calculate the strength and direction of recent climate and biodiversity changes using reliable global indicators; (2) to describe how climate change alters plant-animal interactions through phenology, range shifts, physiology, and network rewiring; (3) to compare responses in pollination, herbivory, seed dispersal, trophic interactions, and related ecosystem processes; (4) to evaluate implications for ecosystem carbon, resilience, regeneration, and environmental services; and (5) to identify defensible management interventions and monitoring priorities under non-stationary environmental conditions. The review addresses five questions: (1) what is the magnitude and direction of recent global climate and biodiversity change; (2) through which biological mechanisms do these changes propagate into plant-animal interactions; (3) which interaction types, taxa, and ecosystem contexts appear most sensitive; (4) how do interaction changes affect regeneration, food-web stability, carbon storage, and resilience; and (5) which conservation and environmental-management interventions are most defensible under uncertainty?

Methodology

This article is a structured narrative evidence review, not a new field experiment, systematic review, or meta-analysis. The synthesis draws on authoritative global indicator reports and peer-reviewed studies cited in the manuscript. The submitted source document did not contain a reproducible search protocol, database exports, duplicate-removal log, screening decisions, or a study-level extraction sheet. Consequently, exact Scopus or Web of Science search strings, numbers of records identified, screened, excluded, and included, and PRISMA flow counts cannot be reconstructed and are not reported. No pooled effect sizes are calculated. The review distinguishes observed global indicators, biological mechanisms reported in primary studies, and scenario-based model projections; it retains numerical comparisons only when it can identify the source and metric. A PRISMA flow diagram is therefore not claimed.

The physical-indicator scope covers the instrumental climate record, with CO_2, biodiversity, ocean heat, sea level, and vegetation assessed over the periods available from their respective sources. The Living Planet Index record, standardized from 1970 to 2020, is used for monitored vertebrate population abundance trends. The literature synthesis includes terrestrial, freshwater, wetland, and coastal ecosystems, focusing on plant-animal interactions directly or indirectly influenced by environmental change. Annual Mauna Loa CO_2 means for 1960–2024 were obtained from the NOAA Global Monitoring Laboratory annual mean series [21]. We applied ordinary least squares (OLS) regression to these 65 annual observations, with calendar year as the predictor and annual mean CO_2 concentration as the response. The estimated slope was 1.6705 ppm yr^{-1} (standard error 0.0284; 95% confidence interval 1.6137–1.7273; $R^2 = 0.9821$; $F_{(1, 63)} = 3452.92$; $p = 9.62 \times 10^{-57}$). The 2024 Mauna Loa annual mean was 424.61 ppm. For Fig. 1, annual global land-ocean temperature anomalies for 1990–2024 were taken from NOAA Global Temp v6.1 and expressed relative to the 1850–1900 mean of that same data set [24]. The 2024 value from this updated series is 1.42 °C; it differs slightly from the 1.46 °C value in the earlier NOAA 2024 assessment [1] because the underlying dataset has been updated. The submitted manuscript provided only summary values for the Living Planet Index, so it claims no OLS statistics for that indicator. The Living Planet Index is interpreted as an index of monitored vertebrate population abundance, not as a census of all species. The analytical framework separates three evidence classes: (1) observed global environmental and biodiversity indicators; (2) biological mechanisms demonstrated or supported by primary studies; and (3) scenario projections. The synthesis reports phenological and spatial response rates as stated in the cited literature and does not pool them into new effect estimates. Network analysis, interaction observations, reproductive and recruitment measurements, and hierarchical or structural equation models are discussed as methods used in the wider literature, rather than analyses newly conducted in this review. Table 1 summarizes the evidence sources and their analytical roles.

We analyzed only atmospheric CO_2 using a fitted OLS model because a complete annual Mauna Loa series was available for 1960–2024. The estimated increase was 1.6705 ppm yr^{-1} (SE = 0.0284; 95% CI = 1.6137–1.7273; $R^2 = 0.9821$; $F_{(1, 63)} = 3452.92$; $p = 9.62 \times 10^{-57}$). The reported 2024 Mauna Loa annual

Table 1 Evidence and data sources used in the synthesis.

Source family	Indicator / evidence	Analytical role	Status
NOAA NCEI	Land–ocean temperature anomaly	Climate trend	Observed
NOAA GML / Mauna Loa	Atmospheric CO_2	Atmospheric driver	Observed
WMO	Ocean heat and sea level	Ocean/coastal pressure	Observed
WWF / ZSL	Living Planet Index	Biodiversity trend	Observed
MODIS / WMO	Mean NDVI	Vegetation response	Observed
Primary literature	Phenology, pollination, herbivory, dispersal	Mechanistic synthesis	Mixed
Weiskopf et al. [23]	Plant-biodiversity-related vegetation-carbon loss under SSP1/RCP2.6 and SSP5/RCP8.5	Scenario-based long-term carbon-loss exposure	Modelled scenario
GBIF	Species occurrences	Proposed spatial monitoring	Method option

mean was 424.61 ppm [21]. Temperature and Living Planet Index values are presented as reported annual observations or endpoints; no additional regression is claimed for these indicators (Fig. 1; Fig. 3). Regression estimates are reported in Table 2.

For spatial redistribution, Vitasse et al. [22] synthesized observations for 2,133 species in the European Alps. They reported mean upslope shifts in optimum elevation of approximately 18–25 m per decade; leading edge shifts were 17–40 m per decade for plants and 47–91 m per decade for animals. The estimated isotherm velocity was 62–71 m per decade, calculated from observed regional warming since 1970 and the local temperature lapse rate. This is a historical physical climate velocity estimate, not a future projection under an SSP scenario. Because the biological estimates refer to different taxa and distribution metrics, the comparison indicates regional disequilibrium and should not be treated as a like-for-like test or as proof of dispersal limitation. Carbon-loss estimates are scenario projections, not observed losses. Weiskopf et al. [23] report long-term vegetation-carbon-loss exposure of 7.44–103.14 Pg C under the global-sustainability scenario (SSP1/RCP2.6) and 10.87–145.95 Pg C under the fossil-fueled development scenario (SSP5/RCP8.5). These ranges refer to modeled carbon losses associated with plant biodiversity decline within remaining habitat, in addition to direct carbon losses caused by land-use change. They are not single-point forecasts or measured emissions.

Results and Discussion

This section integrates observed global environmental and biodiversity signals, response magnitudes reported in published studies, and mechanistic implications for ecological interactions and resilience. These evidence classes remain distinct so that measured indicators are not conflated with regional literature estimates or scenario projections.

Global environmental signals

The updated NOAA Global Surface Temperature Data set (NOAA Global Temp v6.1) shows a clear rise in annual global land-ocean temperature anomalies over 1990–2024 (Fig. 1). When expressed relative to the 1850–1900 mean of the same data set, the 2024 anomaly is 1.42 °C [24]. This is slightly lower than the 1.46 °C value reported in the earlier NOAA 2024 assessment [1], reflecting an updated data release rather than a change in the observed trend. The NOAA Global Monitoring Laboratory annual mean at Mauna Loa reached 424.61 ppm in 2024; the 1960–2024 OLS analysis indicates an

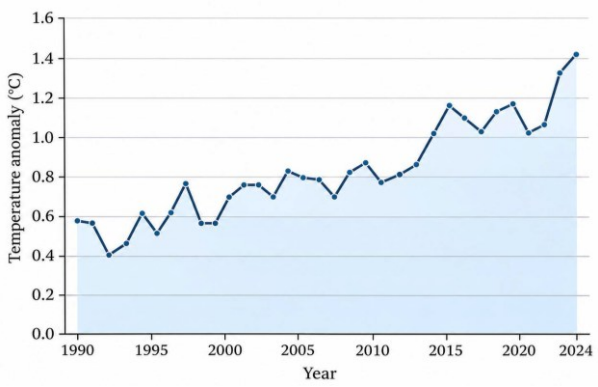

Fig. 1 Annual global mean land–ocean temperature anomalies, 1990–2024, relative to the 1850–1900 baseline. Annual values are from the NOAA Global Surface Temperature dataset (NOAA Global Temp), version 6.1; the 2024 anomaly is 1.42 °C.

Table 2 Ordinary least-squares regression of annual Mauna Loa CO_2 concentration on year, 1960–2024.

Model statistic	Estimate
Annual observations (n)	65
Slope, β_1 (ppm yr^{-1})	1.6705
Standard error of slope	0.0284
95% confidence interval	1.6137–1.7273
R^2	0.9821
F-statistic	3452.92 (df = 1, 63)
p-value	9.62×10^{-57}
Fitted equation	$CO_2 = -2966.694 + 1.67049 \times Yr$

average increase of 1.6705 ppm yr^{-1} (Table 2; Fig. 2) [21]. The 2024 Living Planet Index reports an average 73% decline in relative abundance across 34,836 monitored vertebrate populations representing 5,495 species between 1970 and 2020 (Fig. 3) [4]. This statistic reflects monitored population abundance and should not be interpreted as a 73% loss of all species or individual animals.

Phenological and spatial responses

Phenological responses differ among taxa. The source synthesis reports average advances of approximately 5.2 days per decade for temperate trees, 4.1 days per decade for shrubs, and 2.1 days per decade for migratory birds (Fig. 4). This difference is ecologically plausible because many temperate trees track local spring thermal accumulation, although chilling and photoperiod also influence their responses. Long-distance migratory birds, by contrast, migratory birds often initiate migration through endogenous programs and photoperiodic cues experienced on their wintering grounds, whereas food availability at breeding sites responds to local weather. These cue systems can therefore shift at different rates. The faster reported advance for trees than for migratory birds is consistent with a risk of temporal mismatch between vegetation development, insect availability, and bird arrival; it is not a universal estimate for every species or region [6, 11, 25]. Spatial redistribution also differs among taxa. In the European Alps, Vitasse et al. [22] synthesized observations for 2,133 species and reported mean upslope shifts in optimum elevation of 18–25 m per decade. Leading edge shifts were 17–40 m per decade for plants but 47–91 m per decade for animals, while historical isotherm velocity was 62–71 m per decade (Fig. 5). Because animal leading edges shifted faster than plant leading edges, some animal species may reach higher elevations before their food plants or structural habitat components have become established, creating a potential lag in resource and habitat availability. This interpretation is plausible but not a direct, like-for-like comparison: the estimates cover different taxa and distribution metrics, so they do not prove a universal dispersal constraint or a global animal-plant lag.

Interaction networks and ecosystem carbon

Weiskopf et al. [23] estimate that plant biodiversity decline could expose terrestrial vegetation carbon to long-term losses of 7.44–103.14 Pg C under global sustainability (SSP1/RCP2.6) and 10.87–145.95 Pg C under fossil-fueled development (SSP5/RCP8.5). The ranges are scenario-specific and reflect uncertainty in biodiversity-biomass relationships and species-area assumptions. They refer to carbon losses within

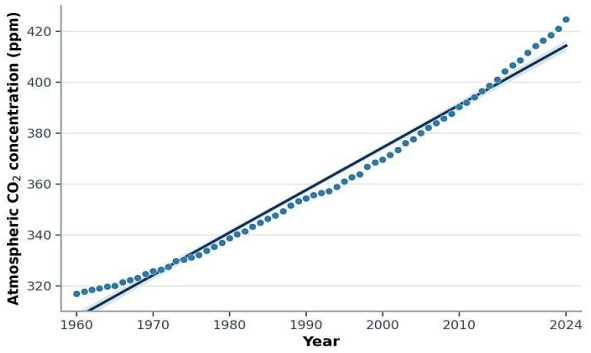

Fig. 2. Annual mean atmospheric CO_2 concentration at Mauna Loa Observatory, 1960–2024. Points represent annual means; the solid line shows the OLS fit and the shaded band the 95% confidence interval for the fitted mean. Slope = 1.6705 ppm yr^{-1}; $R^2 = 0.9821$; $F(1, 63) = 3452.92$; $p = 9.62 \times 10^{-57}$. Source: NOAA Global Monitoring Laboratory.

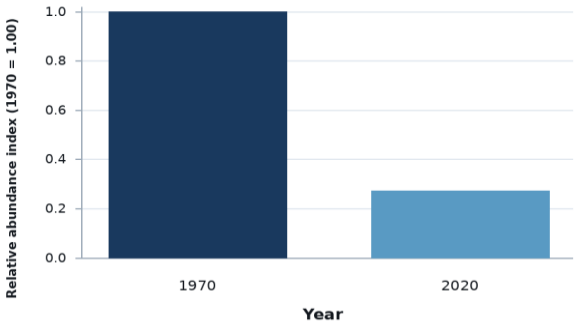

Fig. 3. Living Planet Index endpoints (1970 = 1.00; 2020 = 0.27), representing a 73% decline in average monitored vertebrate population abundance between 1970 and 2020. No annual time series is inferred. Source: WWF/ZSL.

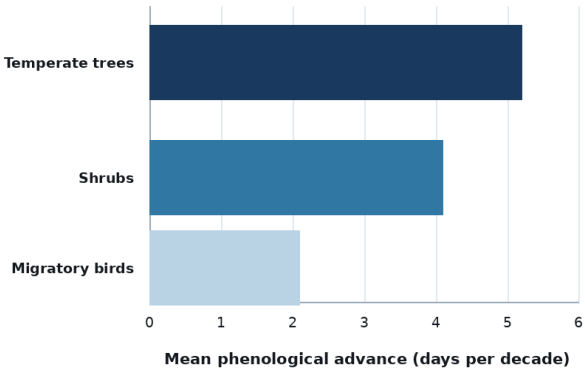

Fig. 4. Reported average phenological advances for temperate trees (5.2 days per decade), shrubs (4.1 days per decade), and migratory birds (2.1 days per decade). Values are literature-reported summaries, not pooled estimates from this review.

Table 3 Scenario-specific estimates of long-term vegetation-carbon-loss exposure associated with plant-biodiversity decline.

Scenario	Pathway	Estimated carbon-loss exposure (Pg C)
Global sustainability	SSP1/RCP2.6	7.44–103.14
Fossil-fueled development	SSP5/RCP8.5	10.87–145.95

Note: These are modeled long-term losses of vegetation carbon within remaining habitat, additional to direct land use change effects; they are not observed emissions. The ranges reflect uncertainty in biodiversity-biomass relationships and species-area assumptions [23].

Table 4 Priority recommendations for interaction-centered environmental management.

Priority	Recommended action
Protect connectivity	Maintain habitat corridors, stepping stones, and climate refugia so plants and animals can track environmental change.
Restore interaction function	Evaluate restoration using pollination, seed dispersal, herbivore regulation, recruitment, and recovery metrics, not species counts alone.
Reduce non-climatic stressors	Prioritize fragmentation, pesticides, invasive species, pollution, and overharvesting because these pressures can reduce adaptive capacity.
Rebuild dispersal networks	Protect and, where appropriate, reintroduce effective large-bodied seed dispersers and reconnect fragmented habitats.
Strengthen phenological monitoring	Pair plant flowering/fruiting observations with pollinator, herbivore, and disperser activity to detect mismatch early.
Integrate climate and biodiversity policy	Avoid planning climate adaptation, land-use management, and biodiversity conservation separately when mechanisms interact.
Use standardized long-term datasets	Develop open repositories for interaction matrices, traits, phenology, environmental covariates, and reproducible analytical code.
Validate network indicators	Test composite indices against independent measures of resistance, resilience, reproduction, recruitment, and ecosystem function before policy adoption.

remaining habitat, above direct land-use change effects, and should not be interpreted as observed carbon emissions or as a single deterministic forecast (Table 3; Fig. 7). In tropical forests, large-seeded tree species often have greater wood density and stature, traits associated with higher carbon storage. Where large herbivores decline, recruitment of these trees may decline, and regeneration may become more dependent on smaller-seeded species dispersed by surviving generalists. Over time, this compositional shift can lower community-level wood density and carbon storage potential [7, 18, 26]. Fig. 6 illustrates this conceptual pathway; it is not a quantitative model. A change in species composition does not automatically represent successful ecological rewiring. Rewiring can buffer disturbance when surviving species establish new interactions that maintain comparable pollination, seed dispersal, or trophic functions. The network becomes functionally weak, or dissolves, when specialists disappear, alternative partners are absent, or replacement links are less effective. The distinction matters because an increase in observed links can coexist with losses in interaction strength, timing, or ecological function. Functional redundancy should therefore be evaluated through interaction identity, strength, phenological overlap, reproductive outcomes, and recruitment rather than inferred from taxonomic similarity alone [11–14, 28]. Disturbance can favor broad-niche or disturbance-tolerant species while reducing ecological distinctiveness. In some temperate forests, overabundant deer selectively browse understory vegetation, alter woody regeneration, and shift plant community composition [29]. Globally, the spread of non-native plants has contributed to declining floristic turnover and biotic homogenization across regions [30]. Introduced species have also reduced biogeographic compartmentalization in global plant frugivore networks [27]. These examples show why

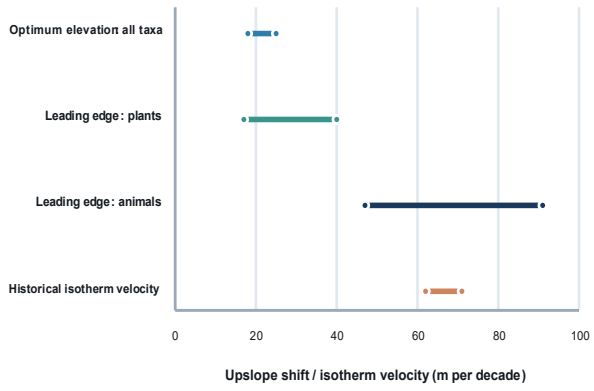

Fig. 5 Published estimates of elevational shifts and historical isotherm velocity in the European Alps: optimum-elevation shifts across taxa (18–25 m per decade), leading-edge shifts for plants (17–40 m per decade) and animals (47–91 m per decade), and estimated historical isotherm velocity (62–71 m per decade). Biological and physical estimates use different metrics and are indicative rather than a like-for-like test.

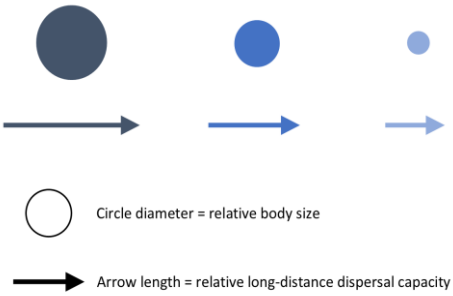

Fig. 6 Conceptual illustration of how loss of large-bodied herbivores can reduce long-distance seed dispersal. Circle diameter represents relative disperser body size; arrow length represents relative long-distance dispersal capacity. The diagram is conceptual and does not represent measured values.

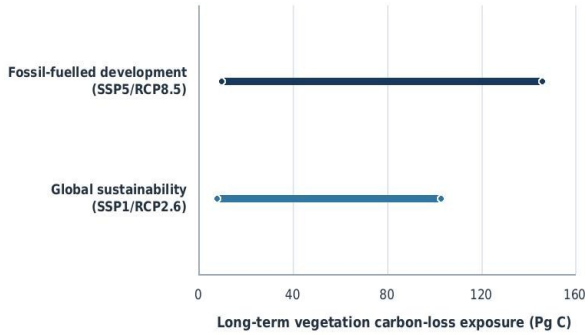

Fig. 7 Scenario-specific ranges of long-term vegetation-carbon-loss exposure associated with plant biodiversity decline: 7.44–103.14 Pg C under global sustainability (SSP1/RCP2.6) and 10.87–145.95 Pg C under fossil-fueled development (SSP5/RCP8.5). Values are modeled exposure ranges within remaining habitat, not observed emissions.

generalist or disturbance-tolerant species may maintain some local interactions without replacing specialists' ecological roles. The result can be a simpler and more homogeneous network rather than a functionally equivalent, resilient ecosystem. Environmental management should safeguard interaction processes as well as species occurrences. Priorities include maintaining habitat corridors, stepping stones, and climate refugia; protecting seasonal flowering and fruiting resources; conserving effective large-bodied herbivores and predators; and reducing fragmentation, pesticide exposure, invasive species, pollution, and overharvesting. Monitoring should pair plant flowering and fruiting observations with pollinator, herbivore, and dispersal activity so that mismatches can be detected early. Evaluate restoration success through pollination, seed dispersal, herbivore regulation, reproductive success, recruitment, and recovery, alongside species richness (Table 4). Interpretation is constrained by taxonomic and geographic biases in monitoring, uneven observation periods, and differences in sampling intensity. Network metrics are sensitive to sampling effort, and apparent rewiring may partly reflect changes in observation rather than ecological change. This narrative review does not provide a harmonized effect size database or a causal estimate linking a specified amount of warming to a universal plant-animal response. Land use change, pollution, natural variability, adaptation, and uneven data coverage remain important sources of uncertainty. Carbon-loss ranges are scenario-dependent and reflect uncertainty in species area relationships and biodiversity biomass functions. The source manuscript did not contain a documented systematic search audit trail; accordingly, the article is presented as a narrative evidence review rather than a PRISMA systematic review or meta-analysis.

Conclusions

Plant-animal interactions are a key dimension of ecosystem resilience under climate change. The evidence reviewed here links great physical environmental change with heterogeneous biological responses, including phenological shifts, spatial redistribution, physiological change, and interaction-network reorganization. The ecological consequences depend not only on whether species persist, but also on whether critical interactions continue and retain their functions. Specialist interactions and large-bodied seed dispersers may be particularly vulnerable, while generalist partners can provide temporary buffering where functional alternatives exist. Scenario analyses further indicate that plant-biodiversity decline may reduce long-term vegetation carbon storage, although the magnitude depends strongly on the pathway and assumptions. These findings support interaction-centered environmental management based on long-term monitoring, network- and trait-based assessment, landscape connectivity, native restoration, refutation, and integrated climate-biodiversity planning. Future evidence syntheses should address the review's narrative design and incomplete source-search audit trail through a fully documented systematic search and study-level extraction process.

Conflicts of Interests

The authors have no competing interests in preparing this manuscript.

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