Where the green goes: green-network configuration and the super-additive loss of urban biodiversity under polyuncertainty

Short title: Green-network configuration under urban polyuncertainty

Kiatanantha Lounkaew[1*]

[1] Faculty of Economics, Thammasat University, Bangkok, Thailand

ORCID: 0000-0002-9128-7283

* Corresponding author

E-mail: klounkaew@econ.tu.ac.th (KL)

Abstract

Climate assessment for cities proceeds one pressure at a time, its uncertainty treated as a sum of separable parts. Compound-event research shows this understates risk when drivers are dependent, and urban ecology that habitat arrangement, not quantity, governs which species persist. These have not been joined, so the contribution of green-infrastructure configuration, as against extent, to ecological loss under polyuncertainty, the condition in which several stressors act at once and interact, is unknown. First we measure co-occurrence in the hazards 1,070 cities disclosed to CDP in 2021. Among the 871 naming at least one, the mean names 3.60 of ten families, and extreme heat and water scarcity are named together by 33.8 percent against 27.2 percent under independence, a lift of 1.24 against a fixed-margins null of 1.11 at z equal to 4.7. The dependence is structured, since dry-regime hazards cluster while wet-regime hazards separate, so the pair the model compounds is empirically motivated and blanket super-additivity is not. Second, a patch-network metacommunity model compares fragmented, corridor, and redundant networks across seven scenarios. Under an imposed super-additive interaction regime, the model produces a joint heat-drought loss approximately 1.3 times the sum of the corresponding single-stressor losses. The configurational consequence, by contrast, is emergent. Holding total green area constant, configuration is second-order under any single stressor and first-order under polyuncertainty, the fragmented network falling to a health index of 0.29 against 0.53, while corridors and pocket parks raise it to 0.57 and 0.61 against 0.34 for enlarging its isolated parks.

Keywords: urban climate; compound events; polyuncertainty; green infrastructure; landscape connectivity; metacommunity; ecosystem services; climate adaptation; urban planning

1. Introduction

Climate science has known for more than a decade that hazards assessed one at a time are hazards underestimated. When two drivers are positively dependent in their tails, the probability of their joint exceedance is materially higher than the product of their marginals, so an independence assumption produces a downward-biased loss estimate, and the compound-event program was built to correct that bias [1,2,3,4]. The bias grows rather than holding still, because the joint distribution of drivers shifts as the climate warms [3,5], and a decade of work has consolidated the field's typology and assessment machinery [6,7,8]. Yet urban ecosystems, exposed to heat, drought, fragmentation, invasion, and pollution in the same years, are still assessed one driver at a time, each against a background in which the others are held constant.

The mismatch is visible in this journal. Two recent essays partition the uncertainty attaching to climate projection into "three additive sources of uncertainty" [9], and although the same author later names "their potential interactions in driving unexpected tipping points" as something an assessment ought to include, he does not carry that interaction into the analysis [10]. An opinion piece on urban climate modeling observes that "Uncertainty is further compounded by interdependencies between ECVs such as temperature, humidity, wind, and anthropogenic activity", then concludes that "No standardized framework exists for transparent uncertainty integration" [11]. A framework paper tested the interaction this paper is about, between climatic stress and structural capacity, and reported that "The interaction is statistically negligible", on a synthetic testbed rather than any real landscape [12]. And a review of the maps through which such work reaches policy makers found that of sixty-six studies, twenty-six reported no uncertainty and three put it on the map [13]. Additivity is not a straw position. It is a working assumption, tested once and not rejected, and the framework that would test it properly is acknowledged to be missing.

Whether additivity holds matters most where a city has something to decide. Cities are ecosystems in their own right, coupled human and natural systems whose ecological fabric delivers cooling, stormwater retention, pollination, and the everyday contact with living things on which health depends [14,15,16]. The green infrastructure holding that fabric together is a piece of urban capital whose configuration can be planned, and planning it is one of the few climate levers a municipal government controls outright. The question is therefore narrow and practical. Given that a city holds some fixed quantity of green, does the spatial configuration of that green determine how much biodiversity and how many ecosystem services survive when several stressors act at once? If stressors were additive and disturbances local, the quantity of green would be a sufficient statistic and configuration a second-order refinement to be settled on amenity or cost grounds. The claim tested here is that under compounding stress this is exactly wrong, and that configuration moves from the margin to the center.

The question falls between two literatures. The urban metacommunity literature has shown that the spatial arrangement of habitat, and not its quantity alone, governs which species persist in a fragmented city, but it has studied this along single gradients of urbanization rather than under compounding stress, and it has not held green area constant while varying configuration across a graded ladder [17,18,19,20]. The urban multiple-hazard and ecological-resilience literature has shown that the joint action of coincident stressors is nonlinear and can cross thresholds, but it treats the landscape as a given to be assessed rather than a design variable, and carries no metacommunity mechanism from compounding stress to biodiversity [21,22,23]. Theoretically, the redundancy-and-connectivity vocabulary of urban resilience and the rescue-and-recolonization mechanism of metacommunity ecology describe the same buffering capacity from two sides, without having been joined or extended to the compounding case [24,25]. This paper closes both gaps, in a way that is deliberately transparent rather than ambitious.

It does so in two steps, and the first disciplines the second. A model that compounds heat with drought is worth building only if cities really face heat and drought together, which is measurable rather than assumable, so we measure it in the hazards 1,070 cities disclosed to CDP in 2021 [26]. That measurement turns out to constrain the model, because the dependence among urban hazards runs in particular directions rather than across the board. The simulation then permits a decomposition a two-way comparison would not: because the corridor network differs from the fragmented network in connectivity while the redundant network adds redundancy on top of the same connectivity, the first contrast isolates connectivity and the second isolates the marginal contribution of redundancy at fixed connectivity, so the result says which configurational property matters at the margin rather than only that configuration matters.

The framework yields predictions a field program could refute, and stating them before the results lets the reader hold the model to them. First, the biodiversity gap between a well-connected and a fragmented network of equal area should widen as the number of co-occurring stressors rises. Second, that gap should emerge with a lag, since the mechanism producing it is the failure of recolonization after disturbance rather than an instantaneous mortality difference. Third, connectivity-building interventions should outperform area-enlarging interventions of equal size under compounding stress but not under any single stressor. Each is observable with patch-network maps and species-occupancy data, and the failure of any one would count against the framework.

Two limits belong at the outset. The model is calibrated to no city, and its parameters are chosen to exercise the mechanisms rather than to reproduce a measured landscape, which is the appropriate posture while the empirical base for calibrated urban ecological prediction is still being assembled [16,27]. And the assumption the model rests on divides into two halves that are not on the same footing. The half that says stressors arrive together is measured here, through what cities disclose, and reported in Section 3.1. The half that says their joint effect exceeds the sum of their separate effects is imposed, since establishing it would require city-scale damage data resolved by stressor combination that does not yet exist, and it is taken from the empirical multiple-hazard literature. What the model contributes is the size of the compound effect against an additive baseline and, more importantly, the dependence of that effect on configuration, neither of which is imposed. The distinction between what is assumed and what is emergent runs through the paper, and the second carries the contribution.

2. Materials and methods

2.1 The urban ecosystem polyuncertainty framework

We define urban environmental polyuncertainty as the standing condition in which several environmental stressors act on a city's ecosystems simultaneously, interact so that their combined effect departs from the sum of their separate effects, and evolve continuously rather than arriving as discrete shocks. Each of its three elements is grounded rather than asserted: multiplicity, that cities face heat, drought, fragmentation, invasion, and pollution together rather than in sequence [28,29]; interaction, the compound-event finding that dependent drivers produce joint effects larger than their separate effects added together [2,4,22]; and continuous evolution, the dynamic-ecology finding that the urban disturbance regime is itself changing, so a static assessment describes a landscape that no longer exists by the time it is used [30,31]. The condition is not a compound event, which is a realized combination of hazards, nor deep uncertainty, which is a condition of the analyst rather than the system [32,33,34]. It is the environment a city inhabits in the quiet years as well as the bad ones. Fig 1 sets out the framework's three parts. Four families of interacting stressor, amplified by super-additive compounding, act on the urban ecosystem. The green network, characterized by connectivity, redundancy, and patch area, buffers the ecological response of local extinction, colonization, and rescue, which in turn determines biodiversity and the ecosystem services that follow.

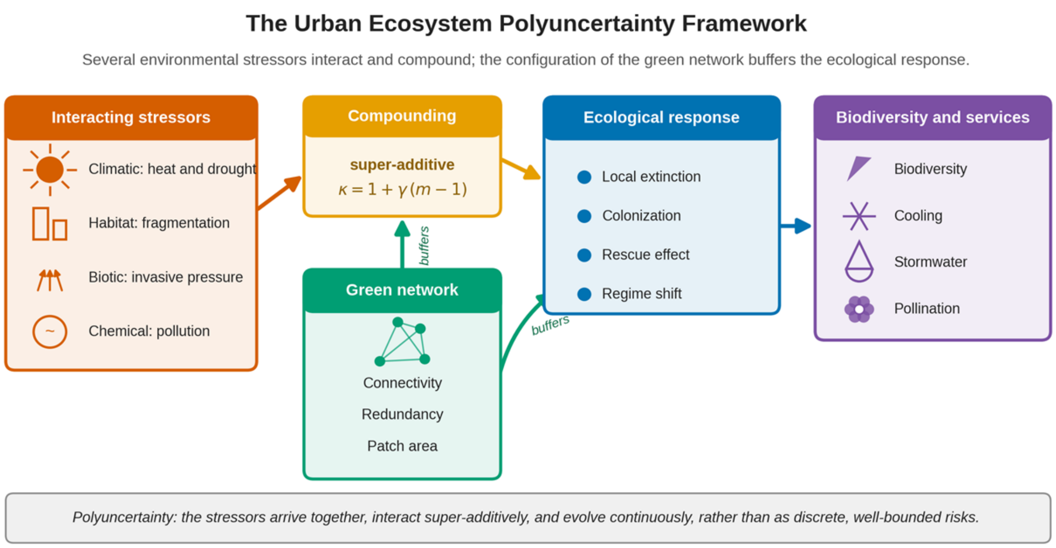


Fig 1. The urban ecosystem polyuncertainty framework. Four families of interacting stressor, amplified by super-additive compounding, act on the urban ecosystem. The green network, characterized by connectivity, redundancy, and patch area, buffers the ecological response of local extinction, colonization, and rescue, which in turn determines biodiversity and the ecosystem services that follow.

The first part is the set of stressors, in four families: climatic stress as heat and drought, habitat stress as fragmentation and development, biotic stress as invasive pressure, and chemical stress as pollution [28,29]. What makes the condition polyuncertain rather than merely multi-hazard is that these families do not stay in their lanes. Drought lowers vegetation's resistance to invasion, development that fragments habitat also concentrates heat, and warming accelerates the demographic changes that determine which species persist, so the joint effect exceeds the sum of the parts and the parts themselves are moving [22,35]. That is why a framework organized around interaction is required rather than a longer list of hazards.

The second part is the green network, characterized by three configurational properties. Connectivity is the degree to which patches are reachable from one another through dispersal, the element that turns isolated patches into a functioning metacommunity and whose loss the founding urban-ecology literature identified as the central liability of the fragmented city [25,28]. Redundancy is the degree to which the network spreads habitat across many patches rather than a few, so no single disturbance removes a large share at once, which is the spatial expression of the insurance principle in the resilience literature [16,24,36]. Patch area is the classical determinant of local persistence, since larger patches carry more extinction-resistant populations [18,20]. The three are not independent, and part of the framework's purpose is to show that their relative importance depends on the disturbance regime, with connectivity and redundancy rising precisely as the stressors compound.

The third part is the ecological response. Local extinction removes a species from a patch, colonization re-establishes it from occupied patches nearby, and the rescue effect lowers extinction risk in well-connected patches because immigration tops up their populations, which is the classic trio of the metacommunity account [25,37]. Biodiversity, the mean occupancy of species across the network, then drives cooling, stormwater retention, and pollination, whose stability depends on it and whose delivery is coproduced with the residents who benefit [38,39]. These responses unfold with lags, so a configuration's biodiversity consequence may take decades to appear, which is one reason a snapshot assessment can be dangerously reassuring [30]. The framework's central claim is that configuration sits between the stressors and the response, and buffers it more strongly precisely when the stressors compound.

2.2 The green-network metacommunity model

We instantiate the framework in a spatially explicit patch-network metacommunity model, in the tradition where local extinction and between-patch colonization jointly determine which species persist across a fragmented city [17,18,25,37]. Its annual cycle is shown in Fig 2, and it is released as a self-contained script with a fixed seed, so every number below is exactly reproducible. Each year, stressor intensities are set with drift and compounding, spatially correlated disturbance events strike, local extinction and the rescue effect are resolved, dispersal and colonization follow along the connectivity network, and the ecosystem state and its services are recorded. The cycle repeats over the forty-year horizon.

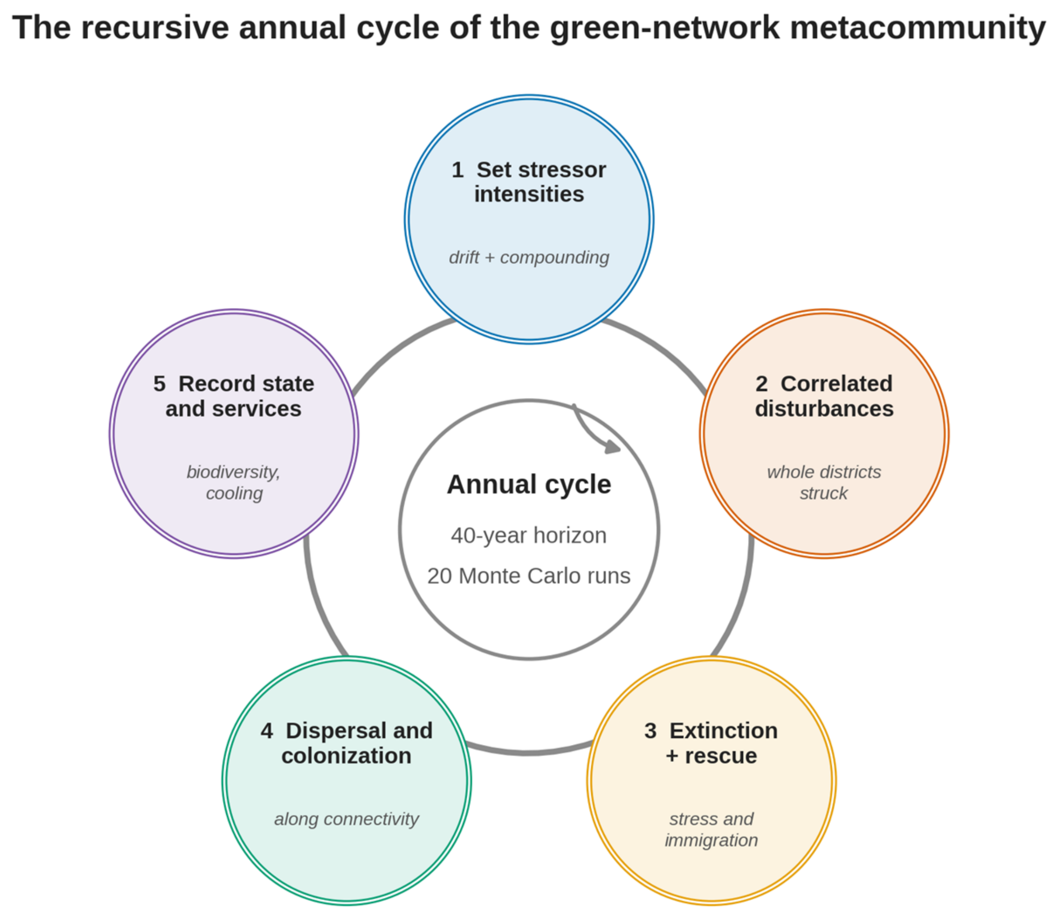


Fig 2. The recursive annual cycle of the green-network metacommunity. Each year, stressor intensities are set with drift and compounding, spatially correlated disturbance events strike, local extinction and the rescue effect are resolved, dispersal and colonization follow along the connectivity network, and the ecosystem state and its services are recorded. The cycle repeats over the forty-year horizon.

The city is a set of habitat patches, each a node with a location and an area standing for size and quality, occupied by thirty functional groups, called species for brevity. Species are heterogeneous in four traits drawn from fixed distributions, a dispersal distance and sensitivities to climatic stress, invasive pressure, and pollution, and a subset are pollinators. The heterogeneity is deliberate, since a model treating all species alike would miss the filtering that produces homogenization and governs which functions survive [19,29]. The state variable is the occupancy matrix recording whether each species is present in each patch [25].

For species i and patch p, connectivity is the propagule pressure arriving from all occupied patches, weighted by their area and by a dispersal kernel that decays with distance,

$$S_{i,p} = \sum_{q \neq p} O_{i,q} \, A_q \exp\left(-\frac{d_{pq}}{\alpha_i}\right),$$

where $O_{i,q}$ is the occupancy of patch q by species i, A_q is the area of patch q, d_{pq} is the distance between patches, and α_i is the dispersal distance of the species. An empty patch is colonized with a probability that saturates in connectivity,

$$C_{i,p} = \frac{S_{i,p}^2}{S_{i,p}^2 + k^2},$$

where k is the connectivity at which the colonization probability reaches one half. An occupied patch suffers a baseline local extinction that rises with the stress load it carries,

$$E_{i,p}^0 = 1 - \exp\left[-e_0\left(1 + 1/2\ \kappa\,\sigma_{i,p}\right)\right],$$

where e_0 is the chronic extinction hazard, $\sigma_{i,p}$ is the stress load defined below, and κ is the compounding factor. Well-connected patches are then partly rescued by immigration, which lowers their realized extinction, the rescue effect that gives connectivity its demographic value [18],

$$E_{i,p} = E^0_{i,p}\left(1 - \rho\,\frac{S_{i,p}}{S_{i,p} + s_h}\right),$$

where ρ is the strength of the rescue effect and s_h is its half-saturation connectivity. The stress load combines the four stressor families weighted by species sensitivities,

$$\sigma_{i,p} = h\,\beta_i^H\,x_p + w\,\beta_i^W + v\,\beta_i^V + c\,\beta_i^C,$$

where h, w, v, and c are the annual intensities of heat, drought, invasive pressure, and pollution, the β terms are the corresponding species sensitivities, and x_p is the heat exposure of the patch, which is lower in large, high-canopy patches, reflecting the moderation of urban heat by vegetated cover [16,40].

Two features carry the polyuncertainty signature, and both are assumptions of the model rather than results of it. The first is super-additive compounding. When m stressors are simultaneously active in a given year, the compounding factor

$$\kappa = 1 + \gamma\,(m - 1)$$

magnifies their joint effect, with γ setting the strength of the interaction. The device imposes, rather than discovers, the nonlinear intensification that compound-event research observes when hazards coincide and that urban ecological-resilience studies observe as threshold behavior [2,21,22]. That literature establishes the sign and threshold character of the interaction but no point estimate of its strength, so γ is set illustratively within the super-additive regime, and the reported compound loss should be read as illustrative of that regime rather than as an estimated effect size.

The second feature is spatially correlated disturbance. Each year brings a Poisson number of events whose rate scales with total stressor intensity; each strikes a disc of the city, and every occupied patch inside it loses its populations with a probability that also rises with compounding. This is how isolated patches are wiped wholesale, and it is what makes connectivity and redundancy worth having, since only a network that spreads risk and recolonizes from survivors recovers from such events [23,24].

The ecological state is summarized by four service dimensions. Biodiversity is the mean occupancy of species across the network. Cooling and stormwater retention scale with the standing green cover, discounted by the prevailing heat, drought, and pollution. Pollination is the mean occupancy of the pollinator functional groups, which depend on reaching flowering resources distributed across the network [18]. These are combined into an urban ecosystem health index,

$$H = w_B B + w_C C_{\text{cool}} + w_S C_{\text{storm}} + w_P C_{\text{poll}},$$

with weights of 0.46 on biodiversity, 0.18 on cooling, 0.14 on stormwater retention, and 0.22 on pollination. Biodiversity takes the largest share because it underpins the stability of the other services, and the qualitative results do not depend on the specific values [16,36]. Because a composite can mask trade-offs, the biodiversity and physical-service dimensions are also reported separately, and the index is best read alongside them.

2.3 Experimental design

The parameters are listed in Table 1. Three configurations, described in Table 2 and shown in Fig 3, hold total green area constant at about thirty-four units, a unit being a dimensionless area rather than a physical hectare, and arrange it differently: five large isolated parks in the fragmented network; smaller parks linked by connective stepping-stones in the corridor network; and many small patches together with those corridors in the redundant network, which is the closest of the three to the intentional patch network the metacity concept proposes [41]. The design partly decomposes the two structural properties, since the corridor network has high connectivity with low redundancy and the redundant network adds redundancy on top of the same connectivity. Each configuration is exposed to the seven scenarios in Table 3, running from a calm baseline through single stressors and pairs to a fully compounding regime, for forty years under twenty Monte Carlo replications with a fixed seed.

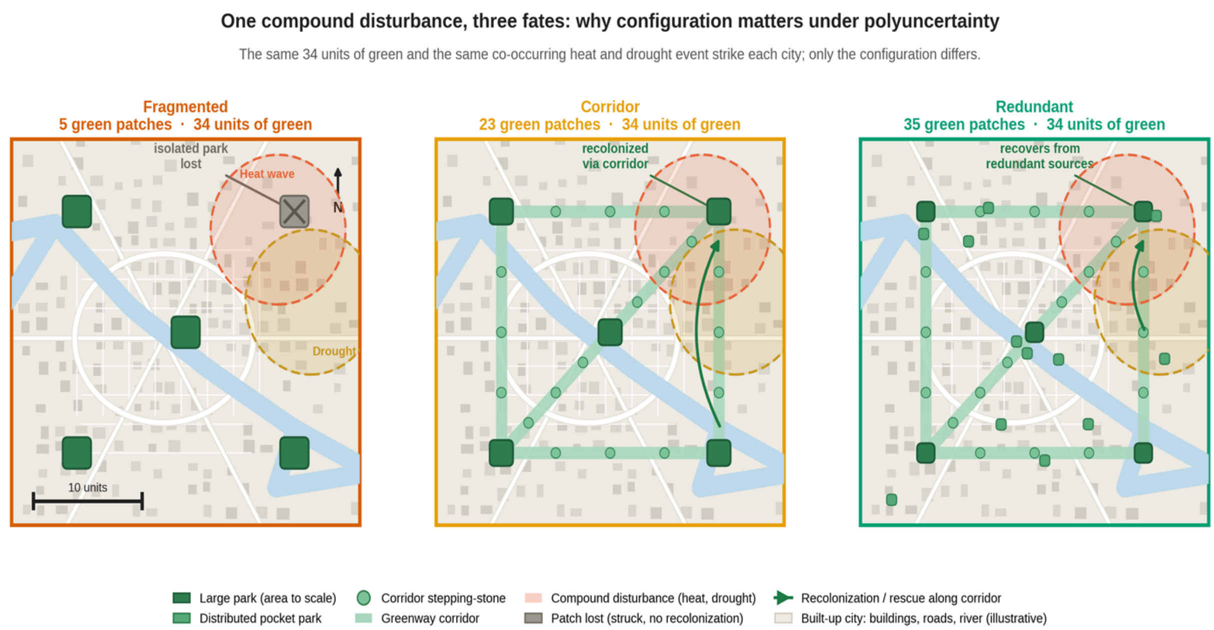


Fig 3. One compound disturbance, three fates. The three green-network configurations are shown inside one hypothetical city of thirty-two by thirty-two units, each holding about thirty-four units of green and differing only in configuration: five large isolated parks in the fragmented network, smaller parks linked by connective stepping-stones along greenways in the corridor network, and a fabric that adds distributed pocket parks in the redundant network. The same co-occurring heat and drought event, drawn as two overlapping disturbance discs, strikes the same

district in every city. In the fragmented city the struck park is isolated and cannot be recolonized, so it is lost; in the corridor and redundant cities the struck patches are recolonized from connected neighbors along the greenways, which is the rescue mechanism through which configuration governs the response to compounding stress. Patch positions and areas are the model's own, with park areas drawn to scale; the buildings, roads, and river are illustrative urban context and are not part of the model, and the disturbance and recovery are shown schematically to convey the mechanism rather than a single simulation year.

Table 1. Parameters of the urban green-network model. Illustrative values chosen to exercise the mechanisms, not calibrated to any city.

Parameter	Symbol	Value	Role
City extent	L	32 units	Landscape for patch placement
Species (functional groups)	S	30	Metacommunity size
Horizon	T	40 years	Long-term dynamics
Monte Carlo replications		20	Stochastic robustness
Chronic extinction hazard	e0	0.03	Background local extinction
Colonization half-saturation	k	0.70	Connectivity for 50 percent colonization
Rescue-effect strength	rho	0.40	Connectivity lowers extinction
Compounding strength	gamma	0.70	Super-additive interaction
Disturbance rate		0.90 per unit stress	Correlated events per year

Parameter	Symbol	Value	Role
Disturbance radius		6.0 units	Spatial extent of an event
Dispersal distance	alpha	2.0 to 9.0 units	Species heterogeneity

Table 2. The three green-network configurations, holding total green area constant.

Configuration	Patches	Connectivity	Redundancy	Description
Fragmented	5	Low	Low	Five large isolated parks
Corridor	23	High	Low	Medium parks linked by stepping-stones
Redundant	35	High	High	Small parks, corridors, and distributed pockets

Table 3. The seven experimental scenarios, from a calm baseline to full polyuncertainty.

Scenario	Heat	Drought	Fragmentation	Invasive	Pollution
Baseline	0.05	0.05	0.00	0.02	0.03
Heat	0.45	0.08	0.00	0.02	0.03
Drought	0.08	0.42	0.00	0.02	0.03
Fragmentation	0.06	0.06	0.35	0.03	0.03
Heat and drought	0.42	0.40	0.00	0.03	0.04
Multiple interacting	0.38	0.34	0.28	0.20	0.10
Full polyuncertainty	0.45	0.42	0.40	0.30	0.18

Note: Entries are annual stressor intensities.

Within a replication the annual cycle proceeds in the order shown in Fig 2. Stressor intensities are set from the scenario and multiplied by a drift factor that rises linearly to 1.6 by the final year, representing the continuous intensification that distinguishes polyuncertainty from a static hazard and that the compound-event literature documents as a shifting joint distribution rather than a fixed one [3,5]. The number of correlated disturbance events in a year is drawn from a Poisson distribution whose mean is the disturbance rate times the total stressor intensity, each event is centered at a uniformly random location, and its radius expands with the compounding factor. Occupied patches within an event lose their populations with a probability equal to the event mortality times the species disturbance sensitivity. Chronic extinction, the rescue effect, and colonization are then resolved as above, and the ecosystem state and services are recorded. Each replication draws a fresh species community and, for the redundant network, a fresh placement of pocket parks, while the five anchor parks and the corridor geometry are fixed. A reduced Overview, Design concepts, and Details protocol for the model is given in S1 Appendix, the full parameter set and the code in S2 Appendix, and a workbook of the numeric series behind every figure in S1 Data.

2.4 Observed co-occurrence of stressors across 871 cities

The model assumes two things about the stressors it compounds: that they arrive together, and that their joint effect exceeds the sum of their separate effects. The second cannot be measured without city-scale damage data resolved by stressor combination, which does not exist, so the paper imposes it and says so. The first can be measured, and this subsection measures it.

The data are the climate hazard disclosures cities made to CDP in the 2021 reporting cycle [26]. The cycle covers 1,070 cities, of which 871 name at least one hazard, and every named hazard falls into one of the ten families listed in Table 4. Each reporting city contributes one row of a binary city-by-family incidence matrix, so the object analyzed is which families a city says it faces, not how severely. For every pair the lift is the observed joint frequency divided by the product of the two marginal frequencies, so a lift of one is independence and a lift above one says the families are reported together more often than independence implies.

Table 4 gives the descriptive statistics the model needs, and three features bear on how the simulation is set up. The first is prevalence. Extreme heat is named by 543 cities, 62.3 percent, and water scarcity by 380, 43.6 percent, so the two stressors the model compounds are the two most widely reported of those with a counterpart in the framework, and 294 cities, 33.8 percent, name both. Climatic stress in one of those forms is present in 629 cities, 72.2 percent. Biological hazards, the closest counterpart to the model's biotic family, are named by 206 cities, 23.7 percent, and chemical change by 96, 11.0 percent.

The second feature is that the mapping to the framework is partial, and pretending otherwise would misrepresent what the data can support. Heat and water scarcity are climatic stress in exactly the sense the model uses. Biological hazards and chemical change are approximate counterparts, defined more broadly in the disclosure than invasive pressure and pollution are in the model. And habitat fragmentation has no counterpart at all, being a land-use process rather than an event a city discloses as a hazard, so that family is not tested here. Six of the ten disclosed families enter only as part of the co-occurrence structure. Of the three framework families that can be observed, 22.5 percent of cities report none, 52.0 percent one, 21.6 percent two, and 3.9 percent all three, which places the scenario ladder in perspective: the heat and drought rung describes a third of disclosing cities, the fully compounding rung a small minority.

The third feature makes the null in the next paragraph necessary rather than decorative. The rarer a family, the broader the reporting of the cities naming it: cities naming flood and sea level rise report 3.32 other families on average, against 4.48 for extreme cold, 4.44 for biological hazards, and 4.16 for chemical change, and between 0.7 and 3.1 percent of cities naming those three rare families name nothing else. Rare hazards are therefore markers of broad disclosure as much as of unusual exposure, and any measure of association that does not hold reporting breadth constant reads that pattern as dependence between the hazards.

Table 4. Descriptive statistics of the 2021 CDP hazard disclosure, by hazard family.

Hazard family	Model stressor family	Cities	Share of the 871	Mean other families reported alongside	Reported alone
Flood and sea level rise	No counterpart	549	0.630	3.32	0.067
Extreme heat	Climatic, heat	543	0.623	3.45	0.024
Extreme precipitation	No counterpart	488	0.560	3.15	0.113
Water scarcity	Climatic, drought	380	0.436	3.71	0.045
Storm and wind	No counterpart	338	0.388	3.69	0.041
Wildfire	No counterpart	225	0.258	3.99	0.040
Biological	Biotic	206	0.237	4.44	0.010
Mass movement	No counterpart	170	0.195	4.08	0.018
Extreme cold	No counterpart	142	0.163	4.48	0.007

Hazard family	**Model stressor family**	**Cities**	**Share of the 871**	**Mean other families reported alongside**	**Reported alone**
Chemical change	Chemical	96	0.110	4.16	0.031

Shares are of the 871 cities naming at least one hazard. The model stressor family column records which of the framework's four families each disclosed family corresponds to, with no counterpart marking families that lie outside the framework. The last two columns show how many other families a city naming this one reports on average, and the share of such cities naming nothing else.

The naive independence benchmark is not sufficient, and this is the methodological point on which the analysis turns. A city reporting six families contributes to fifteen pairs while a city reporting two contributes to one, so heterogeneity in reporting breadth generates positive co-occurrence between every pair even when nothing about the hazards is dependent. We therefore benchmark every lift against a fixed-margins null generated by curveball trades. A trade selects two cities, pools the families unique to each, and redistributes that pool so each keeps the number it began with, preserving both every city's reporting breadth and every family's prevalence while destroying the pairing structure, so the null holds constant everything except the association being measured. We run 5 trades per city per replicate and 2,000 replicates from the fixed seed 20260828, and report for each pair the observed lift, the mean and 95 percent interval of the null, the standardized excess, and a two-sided p value.

Two limitations bound what this can establish, and both belong before the results. The disclosures are self-reported and voluntary, so they measure the hazards a city perceives and elects to report, and the sample is selected toward cities with the capacity to disclose. And the cycle is a single cross-section, so co-occurrence means two families are named by the same city, not that they struck in the same year. The analysis therefore establishes that the multiplicity and dependence the framework posits are present in how cities describe their exposure, which is the premise the model needs, and not that the hazards coincide in time, which would require the design set out in the discussion. It should also be recorded that a companion manuscript by the author, under review elsewhere, uses this same public dataset for a different quantity, the convergence of hazards on shared urban systems, and does not report the pairwise dependence analyzed here.

3. Results

3.1 In real cities, stressors are disclosed together, and heat and water scarcity are positively dependent

Cities do not face one climate hazard at a time. Among the 871 cities naming at least one family in the 2021 CDP cycle, the mean city names 3.60, the median three, and one names all ten, while only 154 cities, 17.7 percent, name a single family; 67.2 percent name three or more and 31.3 percent name five or more, as Fig 4a shows. The multiplicity the framework posits is therefore the ordinary condition of a disclosing city rather than a stylized premise, and an assessment that evaluates one hazard at a time is, for two cities in three, evaluating a third or less of what the city says it faces.

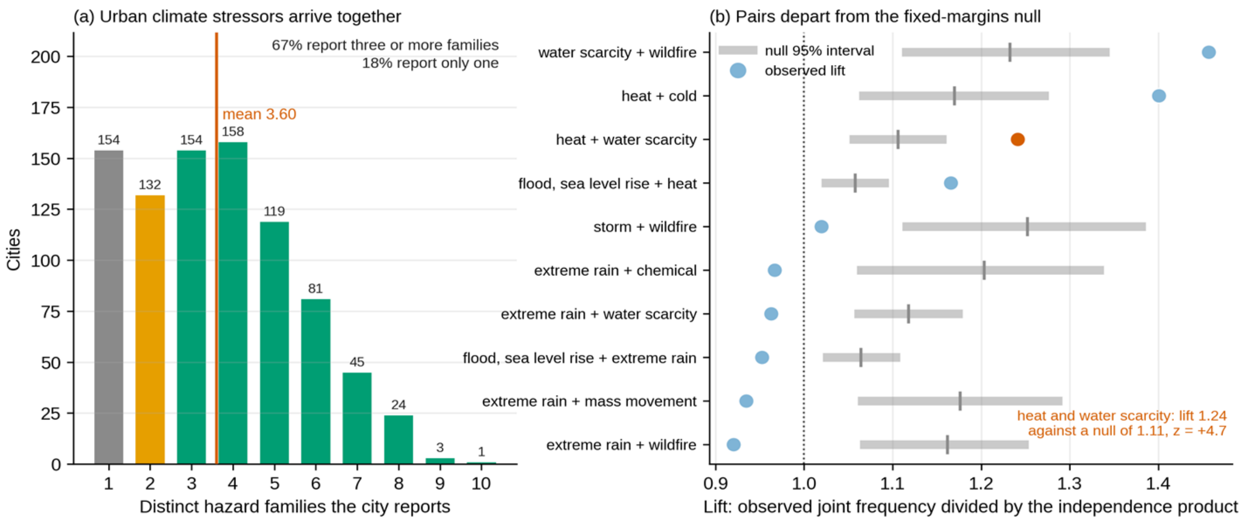


Fig 4. Urban climate stressors are disclosed together, and their pairing is structured. (a) The number of distinct hazard families named by each of the 871 cities that reported at least one in the 2021 CDP cycle. (b) For the ten pairs whose lift departs furthest from the fixed-margins null, the observed lift, shown as a point, against the null 95 percent interval, shown as a bar, with the null mean marked. The dotted line at one is naive independence. Heat and water scarcity, the pair the model compounds, is marked in orange.

Taken at face value the dependence structure is strongly positive, since 39 of the 45 family pairs have a lift above one. That reading is wrong, for the mechanical reason set out in the methods: breadth of reporting alone manufactures positive co-occurrence. Against the fixed-margins null, which holds reporting breadth and family prevalence constant, only 23 of the 45 pairs exceed the null mean, and 16 differ from it at the 5 percent level, seven above and nine below. The pairs that survive are a specific set rather than the whole field.

The pair the model compounds survives, and it survives the strict test rather than the naive one. Extreme heat and water scarcity are named together by 294 cities, 33.8 percent of the sample, against 27.2 percent under naive independence, a lift of 1.24. The fixed-margins null puts that lift at 1.11 with a 95 percent interval from 1.05 to 1.16, so roughly half of the naive excess is the mechanical artifact and the other half is not, and the observed value sits well outside the interval at z equal to plus 4.7, with a two-sided p below 0.0005 on 2,000 replicates. Table 5 reports this pair alongside the nine others that depart furthest from the null. Flood and sea level rise with extreme heat departs furthest of all, at a lift of 1.17 against a null of 1.06 and z of plus 5.6, and water scarcity with wildfire and extreme heat with extreme cold are also positive at z of plus 3.7 and plus 4.4.

Table 5. Pairwise dependence among hazard families, the ten pairs departing furthest from the fixed-margins null.

Pair	Cities with both	Observed share	Independence expectation	Lift	Null mean	Null 95 percent interval	P
Flood and sea level rise and extreme heat	399	0.458	0.393	1.17	1.06	1.02 to 1.10	< 0.0005
Extreme heat and water scarcity	294	0.338	0.272	1.24	1.11	1.05 to 1.16	< 0.0005
Extreme heat and extreme cold	124	0.142	0.102	1.40	1.17	1.06 to 1.28	< 0.0005
Water scarcity and wildfire	143	0.164	0.113	1.46	1.23	1.11 to 1.34	< 0.0005
Extreme precipitation and chemical change	52	0.060	0.062	0.97	1.20	1.06 to 1.34	<0.004
Storm and wind and wildfire	89	0.102	0.100	1.02	1.25	1.11 to 1.39	<0.002
Extreme precipitation and mass movement	89	0.102	0.109	0.93	1.18	1.06 to 1.29	< 0.0005

Pair	Cities with both	Observed share	Independence expectation	Lift	Null mean	Null 95 percent interval	P
Extreme precipitation and water scarcity	205	0.235	0.244	0.96	1.12	1.06 to 1.18	< 0.0005
Flood and sea level rise and extreme precipitation	293	0.336	0.353	0.95	1.06	1.02 to 1.11	< 0.0005
Extreme precipitation and wildfire	116	0.133	0.145	0.92	1.16	1.06 to 1.25	< 0.0005

The negative side of the table is as informative, and it disciplines the model rather than decorating the result. Extreme precipitation is reported with wildfire, mass movement, water scarcity, chemical change, and flood and sea level rise less often than the null implies, at z between minus 3.1 and minus 5.0, and storm and wind with wildfire is likewise negative. The pattern is coherent rather than noisy: hazards of the dry regime cluster and hazards of the wet regime separate from them, which is what a climatological account predicts and a mechanical artifact would not produce. The consequence for the paper is direct. It would be wrong to assume that every pair of urban stressors compounds, and a model that applied super-additivity indiscriminately across all pairs would be assuming something the data contradict. What the data support is the narrower claim the model actually makes, that the specific combination it exercises, heat together with drought, is a combination cities really do face together.

The result weakens under a stricter definition, and the weakening should be reported rather than absorbed. Restricting the matrix to hazards a city reported as having significantly affected it leaves 799 cities and a mean of 3.02 families, and the heat and water scarcity lift falls from 1.24 to 1.18 against a null of 1.10, at z of plus 1.8 and p of 0.073, so on that definition the pair is no longer distinguishable from the null. Two results move the other way, water scarcity with wildfire strengthening to 1.67 at z of plus 5.0 and heat with cold to 1.46 at z of plus 3.9. The honest summary is that the multiplicity finding holds, that the sign and the structure of the dependence hold with it, and that the magnitude of the heat and water scarcity association does not, since it depends on whether one counts hazards a city names or hazards a city says have already hurt it. That is a smaller claim than the model needs to be true, and it is stated here at its true size.

3.2 Compound stressors interact super-additively, and additive assessment understates the loss

The first result concerns the size of the interaction that the model imposes, and it is shown in Fig 5. Because the compounding factor makes super-additivity an assumption, this result is not evidence that compounding is super-additive in the world; that premise is taken from the empirical compound-event and multiple-hazard literatures [2,21,22]. What the result shows is how large the compound effect is relative to an additive baseline under a plausible interaction strength, and therefore how much an additive assessment would miss. On the corridor network, heat alone and drought alone each remove a modest amount of ecosystem health relative to the baseline. Applied together, they remove distinctly more than their separate losses add to, and the compound loss is about 1.3 times the summed single-stressor losses, which places the imposed interaction firmly in the super-additive regime that the empirical literature describes. On the corridor network, the loss in the urban ecosystem health index from combined heat and drought exceeds the sum of the losses from each stressor alone, by a factor of about 1.3. The dotted line marks the summed single-stressor loss.

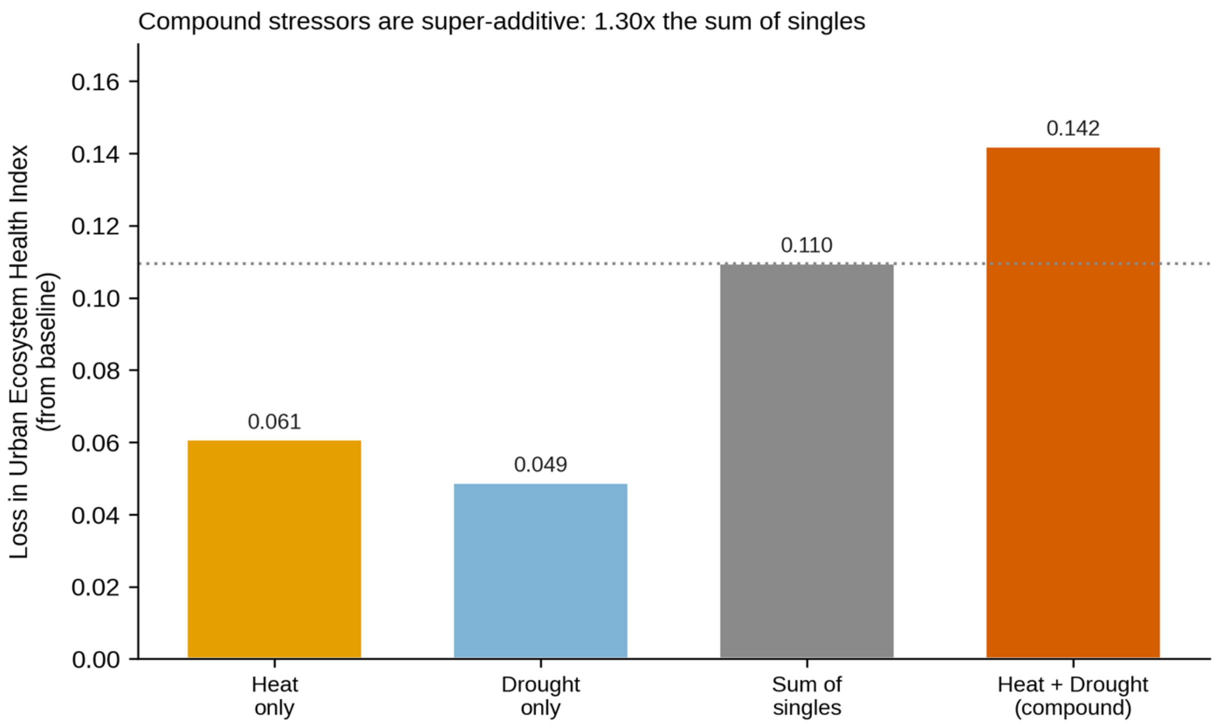


Fig 5. Compound stressors are super-additive. On the corridor network, the loss in the urban ecosystem health index from combined heat and drought exceeds the sum of the losses from each stressor alone, by a factor of about 1.3. The dotted line marks the summed single-stressor loss.

The qualitative point does not depend on the exact interaction strength, and it is worth spelling out for practice. A city commissioning one heat assessment and one drought assessment, each against a background holding the other at baseline, adds two modest losses to obtain a planning figure. Because the joint effect exceeds the sum, that figure is too low, and too low by an amount that grows as the two hazards become more likely to arrive in the same years, which is the direction a warming and drying climate is moving the joint distribution [3,5]. The error is therefore not a fixed bias that could be absorbed into a safety margin once and forgotten. It is a bias that widens with the very trend the assessment exists to anticipate, and this is the sense in which the additive treatment of separable uncertainty sources, whether in climate projection [9] or in resilience assessment [12], is progressively misleading rather than simply incomplete.

3.3 Configuration decides the outcome under compounding stress

The second and central result is emergent rather than assumed. Configuration, holding total green area fixed, governs how much biodiversity and ecosystem health survive, weakly under mild stress and decisively under full polyuncertainty. Nothing imposes that the configurations should diverge; the divergence arises from the interaction of the assumed compounding and correlated disturbance with the connectivity structure. Fig 6 shows final health and biodiversity across all networks and scenarios. At the baseline and under any single stressor the three perform similarly, with only a modest penalty to the fragmented configuration, reflecting the classical liability of isolated patches, whose smaller populations are more extinction-prone and whose recolonization pathways are thin [18,20]. As the scenarios climb toward full polyuncertainty, the networks diverge sharply. Under full polyuncertainty the fragmented network's health index falls to about 0.29 while the redundant network holds near 0.53, and the corridor network sits between them at about 0.48.

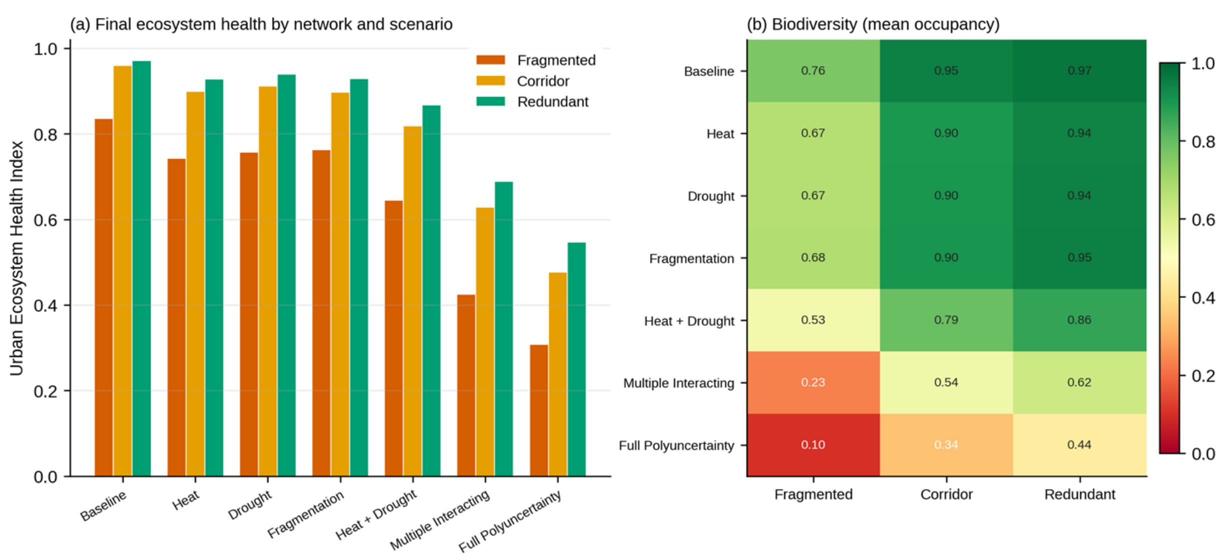


Fig 6. Ecosystem health and biodiversity by network and scenario. (a) Final urban ecosystem health index for each configuration across the scenario ladder; the networks are similar under mild stress and diverge sharply under compounding stress. (b) Biodiversity, measured as mean species occupancy, for each network and scenario.

Because the configurations vary connectivity and redundancy separately, this ordering also decomposes the effect, and the decomposition is the more useful half of the result. The rise from the fragmented to the corridor network, 0.29 to 0.48, is connectivity added at fixed area; the further rise to the redundant network, 0.48 to 0.53, is redundancy added at fixed connectivity. Connectivity therefore carries roughly four fifths of the gap between the worst and best configuration, and redundancy adds a smaller but real increment. This upgrades the finding from the general claim that configuration matters to a statement about which property matters at the margin, and it has a direct planning reading, since connectivity is usually the cheaper of the two to build. The divergence is also not a smooth widening of a small gap but the appearance of a qualitative difference in behavior, in which one network absorbs the compounding stress and another does not, a pattern consistent with the threshold character that urban ecological resilience exhibits when a driver crosses a critical level [21] and with the wider finding that systems under compounding pressure can shift regime rather than degrade smoothly [42].

The divergence is starkest in the biodiversity trajectories under full polyuncertainty, shown in Fig 7. The fragmented network collapses, its mean occupancy falling steadily to about 0.08, roughly one tenth of the network, as isolated parks are struck by disturbance and cannot be recolonized across the intervening matrix. The redundant network retains about 0.45, four to five times as much, and the corridor network again lies between at about 0.34. The shape of the fragmented trajectory is the lagged loss that the dynamic strand of urban ecology has taught the field to expect, in which the full biodiversity cost of a spatial configuration accumulates year on year rather than arriving all at once, because each disturbance that clears an isolated patch removes a population that connectivity would otherwise have replaced [30]. This lag is the second of the three predictions set out in the introduction, and it matters for monitoring, since a city reading its biodiversity indicators in the early years of a compounding regime would see the three configurations performing similarly and would draw the wrong conclusion about which one it should be building. Lines show mean occupancy over forty years and shaded bands the tenth to ninetieth Monte Carlo percentiles. The fragmented network collapses while the redundant network retains most of its biodiversity.

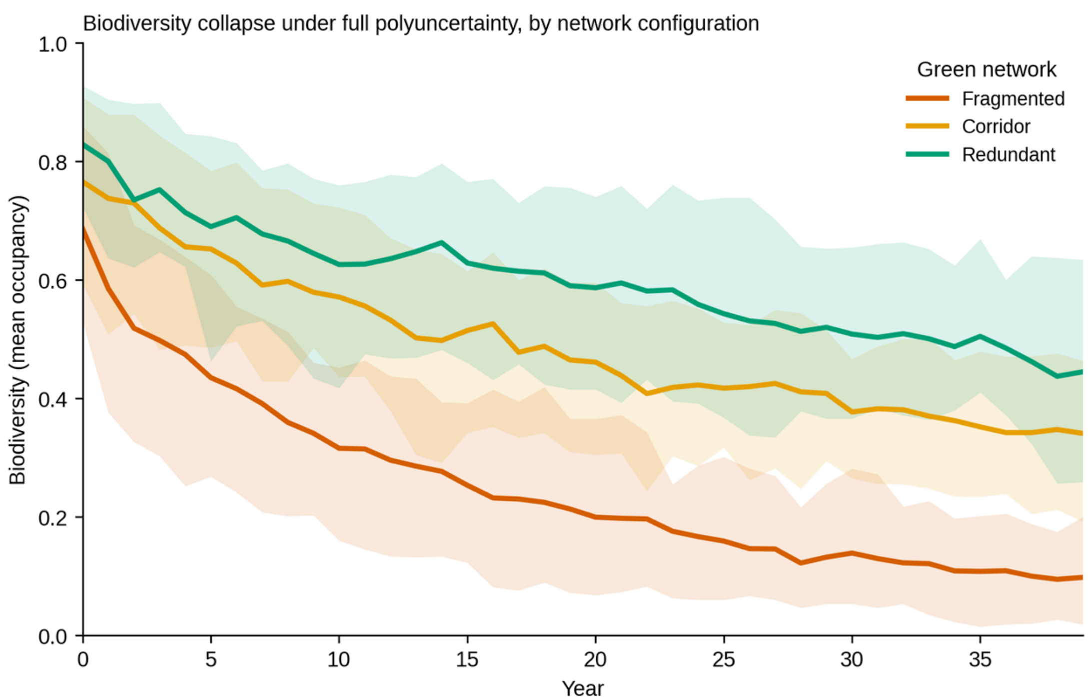


Fig 7. Biodiversity collapse under full polyuncertainty, by network configuration. Lines show mean occupancy over forty years and shaded bands the tenth to ninetieth Monte Carlo percentiles. The fragmented network collapses while the redundant network retains most of its biodiversity.

The collapse is also the model's expression of biotic homogenization, since the survivors are disproportionately mobile, stress-tolerant generalists and the specialists lost are those connectivity would have rescued [29]. Because services rest on biodiversity, they track the biodiversity result. Fig 8 shows the redundant network delivering higher biodiversity, cooling, stormwater retention, and pollination under full polyuncertainty, with pollination most sensitive to configuration because pollinators must reach flowering resources across the network [18]. The services decline together rather than in parallel, because the connectivity that maintains species also maintains the groups that provide them [38,39]. It can be seen that biodiversity, cooling, stormwater retention, and pollination are all higher in the connected and redundant network than in the fragmented one, since the connectivity that maintains species also maintains the functional groups that supply the services.

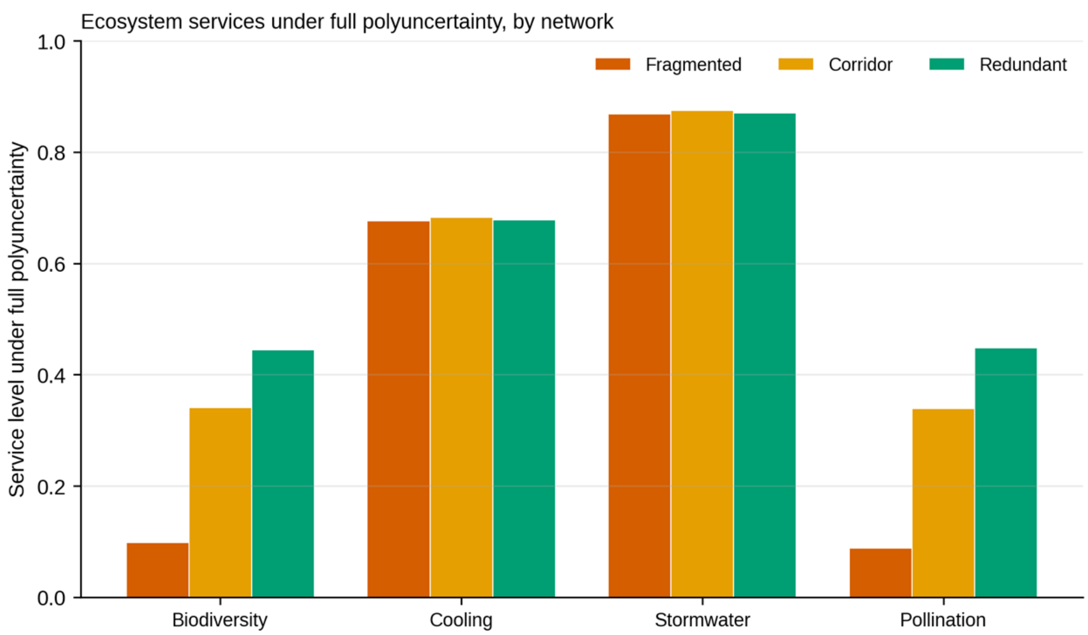


Fig 8. Ecosystem services under full polyuncertainty, by network. Biodiversity, cooling, stormwater retention, and pollination are all higher in the connected and redundant network than

in the fragmented one, since the connectivity that maintains species also maintains the functional groups that supply the services.

3.4 Where green is added matters more than how much

The third result speaks directly to planning. Starting from the fragmented city under full polyuncertainty, we test three restoration strategies that each add a comparable quantity of green in a different spatial configuration, shown in Fig 9. Enlarging the existing isolated parks, which is the intuitive response of adding more of what is already there, barely improves the outcome, raising the health index from about 0.29 to about 0.34. Adding corridors that connect the parks raises it to about 0.57, and adding distributed pocket parks raises it furthest, to about 0.61. The transferable conclusion is the ranking of the strategies rather than the particular index values, which are illustrative: the marginal green unit is worth far more when it is placed to build connectivity or redundancy than when it is used to enlarge patches that remain isolated. This is the third of the paper's predictions, and it is conditional in a way worth emphasizing, since the same ranking does not hold under any single stressor, where enlarging a park raises local population size and does most of what is needed. It is compounding that changes the answer, because compounding acts through correlated disturbance that removes whole patches at once, and against that mechanism a larger isolated patch is a larger thing to lose rather than a safer one. Starting from the fragmented city under full polyuncertainty, enlarging existing parks barely helps, while adding corridors or distributed pocket parks, at comparable green area, restores far more ecosystem health.

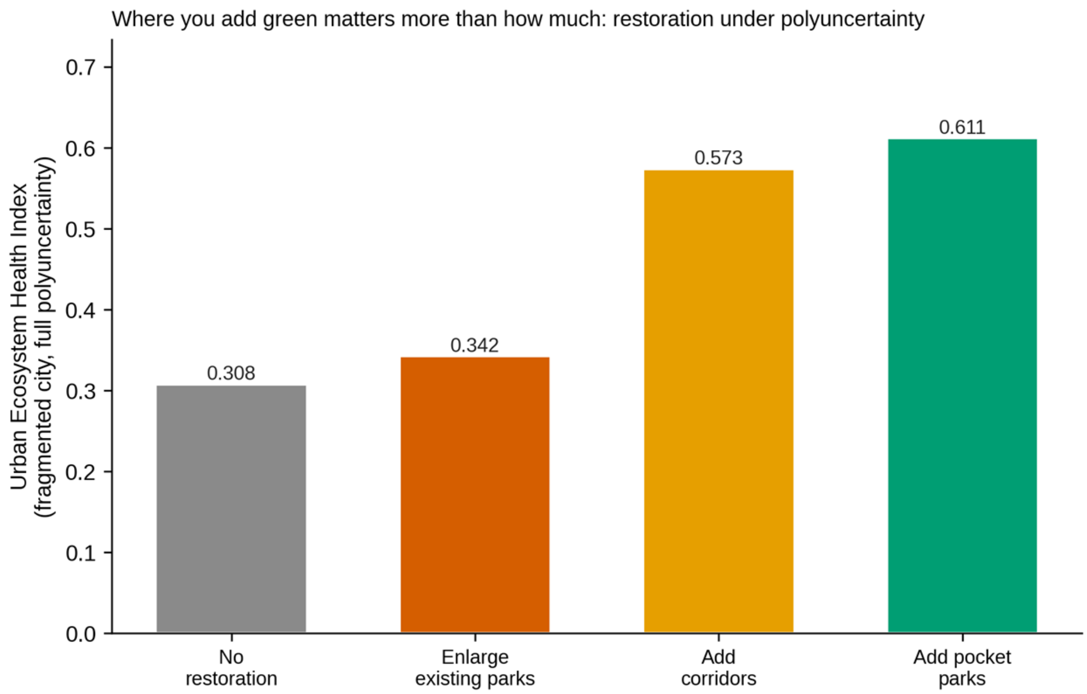


Fig 9. Where green is added matters more than how much. Starting from the fragmented city under full polyuncertainty, enlarging existing parks barely helps, while adding corridors or distributed pocket parks, at comparable green area, restores far more ecosystem health.

3.5 Robustness

The advantage of the connected and redundant network over the fragmented one is robust to the model's parameters within the range tested. Fig 10 reports a one-way sensitivity analysis in which the chronic extinction rate, the colonization half-saturation, the rescue-effect strength, and the compounding strength are each varied by plus or minus twenty-five percent. The network advantage, measured as the difference in final ecosystem health between the redundant and fragmented configurations under full polyuncertainty, stays in a narrow band around its central value of about 0.24 across every variation, and the ordering of the three networks never changes. Each parameter is varied by plus or minus twenty-five percent; the advantage of the redundant network over the fragmented one under full polyuncertainty stays close to its central value and never reverses.

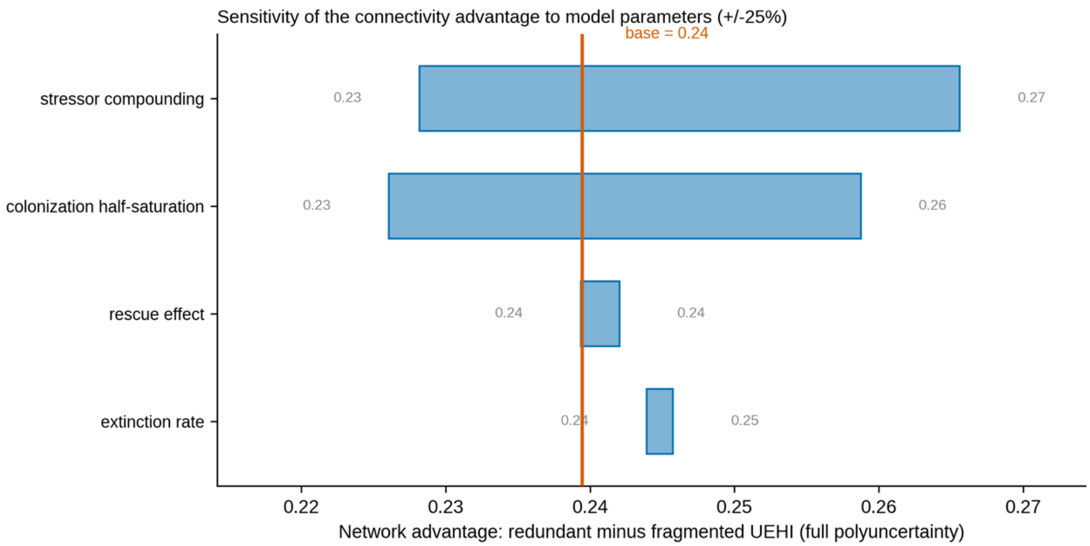


Fig 10. Sensitivity of the connectivity advantage. Each parameter is varied by plus or minus twenty-five percent; the advantage of the redundant network over the fragmented one under full polyuncertainty stays close to its central value and never reverses.

The analysis is one-way and therefore partial, and its limits should be stated rather than left to inference. It does not vary the disturbance rate or radius, which drive the correlated-disturbance mechanism that makes connectivity worth having, nor does it explore interactions among parameters, so what is shown is robustness to single-parameter perturbation rather than to the full parameter space. It varies parameters but not the landscape geometry, since every run uses one stylized layout with fixed anchor parks, so robustness to alternative city geometries remains to be shown. And while the Monte Carlo bands in Fig 7 separate cleanly between the fragmented and redundant networks, no formal test of every pairwise difference against Monte Carlo noise has been conducted. Within that scope the qualitative conclusions are not artifacts of a particular parameter choice, which matters because an illustrative model rests on the stability of its mechanisms rather than the precision of any single number [43].

Table 6 collects the headline figures, reporting for each network the ecosystem health index at the baseline and under full polyuncertainty, the health lost between them, and the final biodiversity under full polyuncertainty. The health lost from baseline to full polyuncertainty is smallest for the redundant network and largest for the fragmented one.

Table 6. Ecosystem health and biodiversity by network.

Network	Health, baseline	Health, full polyuncertainty	Health lost	Biodiversity, full polyuncertainty
Fragmented	0.83	0.29	0.54	0.08
Corridor	0.96	0.48	0.48	0.34
Redundant	0.97	0.53	0.44	0.45

4. Discussion

The results carry a consistent message. Under any single stressor a city’s stock of green infrastructure summarizes its ecological prospects well enough, and configuration is second-order. Under polyuncertainty configuration becomes first-order, and connectivity and redundancy do most of the work. That matters because the conditions under which configuration is decisive are the conditions cities are moving toward [5,22,35,44].

4.1 What follows for assessment practice

The finding that the compound effect exceeds what the separate effects add to has an immediate implication for assessment, and it holds whether the true interaction is as strong as the value assumed here or weaker, provided only that it is super-additive at all. Impact assessment and urban biodiversity monitoring typically evaluate pressures one at a time, and urban ecological research has itself been criticized as fragmented, which makes a joint treatment of interacting stressors the exception [31]. If the joint effect exceeds the sum, as the compound-event and nonlinear-resilience literatures suggest [2,4,21,22], then single-stressor assessment is systematically optimistic, and the optimism grows as the climate makes co-occurrence more likely. A polyuncertainty-aware assessment would test combinations rather than each stressor against a baseline, and would treat the spatial coincidence of hazards, and not their marginal intensities alone, as a variable of interest [8,23].

The disclosure evidence sharpens that recommendation in two ways. It says which combinations are worth testing, since a city testing all forty-five pairs would waste most of its effort on pairs that are independent or that separate, whereas the seven departing positively from the null are a short list. And the list is regime-specific rather than universal, since heat, water scarcity, and wildfire cluster while extreme precipitation separates from all three, so the right combination to stress test in a drying city is not the right one in a wet city. That is more useful than the general injunction to consider compound events, and it comes from a dataset cities already produce, which matters because the binding constraint on assessment reform is usually the cost of the extra analysis rather than the concept.

A second and less comfortable implication concerns how uncertainty itself is decomposed. The convention in climate projection is to partition uncertainty into scenario, model, and internal-variability components and treat them as additive [9,45]. That partition serves questions about the spread of a projected mean. It is less safe for questions about damage, because the mapping from drivers to damage runs through a system whose response to two simultaneous drivers is not the sum of its responses to each, and an additive decomposition of inputs cannot recover a super-additive response of the output. Under the parameters used here, a city assessing its green network with an additive apparatus would understate the damage from co-occurring heat and drought by roughly thirty percent and would misrank the three configurations entirely, since under single stressors they are nearly indistinguishable. The additive partition is not wrong as an accounting of projection spread; it is the wrong object to carry into an impact assessment, and the interaction terms it sets aside are the terms a planner needs [10,11].

The one direct test of this interaction published in this journal returned a null. On a synthetic testbed calibrated to low-income distributions, the interaction between climatic stress and structural capacity was statistically negligible and the resilience surface was well approximated by a sum of independent effects [12]. That result deserves to be read at full strength before it is qualified, and it is a useful corrective to the assumption that interaction effects appear wherever they are sought. Two features of its design bear on how far it travels. Its data were synthetic, so the interaction it tested was one the data-generating process did not contain, and its unit was a rural district rather than a city, so the correlated-disturbance mechanism through which configuration operates here had no counterpart. The question therefore remains open on the empirical side, and settling it requires the city-level test set out below rather than a further round of simulation.

4.2 What follows for planning

The finding that where green is added matters more than how much reframes the central planning choice. The long-standing debate over a few large reserves against many small ones has an answer here that is conditional on the disturbance regime. Under compounding stress with correlated disturbances, distributing green across many connected patches spreads the risk any one disturbance poses and preserves the recolonization pathways that let the network recover, which is the spatial form of the insurance and redundancy principles the resilient-cities literature identifies [24,46,47]. Large parks are not thereby unimportant, since patch area governs local persistence and large source patches supply the colonists the rest of the network depends on [18,28]. It means a planner holding a fixed budget should weight connectivity and redundancy heavily, favoring corridors, stepping-stones, and a distributed fabric of pocket parks and green roofs over enlarging already-isolated reserves, and should conceive the result as an intentional patch network rather than a collection of amenities [41]. Because the model is uncalibrated, this is a direction and a ranking rather than a promise of particular gains.

The lag has its own planning consequence, and it is the one most likely to be missed. Because the biodiversity cost of a fragmented configuration accumulates rather than arriving at once, a city can appear to be coping while drawing down an ecological account that will later be found empty, and the appearance of coping is strongest in exactly the early years when the configuration could still be changed cheaply. This is the ecological form of a general problem in adaptation, that the window in which an intervention is cheap closes before the evidence it was needed becomes visible, and it argues for acting on structure rather than waiting on indicators [34,48,49]. Adaptive policy pathways are the natural instrument, since the decision is not whether to build connectivity but when to commit, and an explicit trigger converts an unanswerable question about the future into an answerable one about a signal [50,51].

The results also carry a distributional implication that the model does not itself test. If the fragmented, poorly connected green networks that fare worst under compounding stress coincide with underserved neighborhoods, as the equity critique of urban resilience and the evidence on unequal access to adaptation would both lead one to expect, then the technical case for connectivity is also a case about who bears the cost of ecological collapse, and the two would need to be addressed together [52,53]. This is not a decorative observation. It changes what the planning lever is, because a connectivity investment that is efficient in aggregate can be regressive in incidence if the corridors are built where the network is already dense, and the ranking of restoration strategies reported above is silent on where in the city each strategy is applied.

4.3 What follows for the idea of urban resilience

The results answer one of the resilience literature's own criticisms. Resilience has been faulted for vagueness, for naming a desirable property without specifying the structure that produces it [52,54]. The model supplies a concrete structural basis for ecological resilience in the city, the connectivity and redundancy of the green network, and shows that this structure separates a network that absorbs compounding stress from one that collapses under it. That is resilience with operational and spatial content, connected to the planning decisions that shape urban form [36,55,56], and it bears on the effort to say what an adaptive capacity consists of, since a structural definition is measurable in a way that a dispositional one is not [57,58,59].

The collapse also has a compositional reading. The fragmented network does not lose species at random; it retains the mobile, stress-tolerant generalists and sheds the sensitive specialists that depend on rescue from neighbors, so the biodiversity that remains is both lower and more homogeneous, which is the signature the urban homogenization literature documents [29]. Homogenization and configuration are therefore linked, since the poorly connected network filters hardest for generalists. The survivors are also those under the strongest selection, so a fuller treatment would let rapid evolutionary change accompany the demographic collapse [35,60,61]; holding traits fixed captures only the demographic half, and the omission does not soften the case for connectivity. None of this arranges itself, finally, since where green is placed and whether it is maintained are decisions of land and urban governance, and the capacity to make them under a changing climate is itself a governance problem [62,63,64,65,66].

4.4 Limitations

Several limitations follow from the model's deliberate simplicity. The landscape is stylized and the species are functional groups rather than real taxa, so the numbers illustrate mechanisms rather than predict outcomes for a named city [27,67]. Super-additivity and its strength are imposed rather than estimated, so only the qualitative direction of the compound effect and its interaction with configuration should be read as general. The disturbance process is generic, where a field application would resolve heat, drought, flood, and outbreak into distinct signatures [4,22]. The service functions are monotone summaries rather than calibrated production functions, the index weights are a modeling choice, and species traits are fixed while urban populations adapt on the timescales the model runs [60]. The sensitivity analysis is one-way and holds the landscape geometry fixed. And the model omits the governance layer that decides where green is placed, which urban ecology would insist is part of the system rather than an add-on [68,69,70]. None of this bears on the qualitative results, which hold across the parameter ranges tested and follow from well-established mechanisms rather than fine-tuned assumptions [25,43].

The empirical section carries limitations of a different kind. The disclosures are voluntary and self-reported, so what is measured is the set of hazards a city perceives and elects to report, and the sample is selected toward cities with the capacity to disclose. The cycle is a single cross-section, so co-occurrence means two families are named by the same city rather than that they struck in the same year, and the analysis speaks to standing exposure rather than the timing of events. And the magnitude of the heat and water scarcity association is sensitive to definition. What survives all three qualifications is the multiplicity result and the structure of the dependence, the two things the model needs, and not a point estimate of how strongly heat and drought coincide.

Taken together, the empirical section establishes the premise of co-occurrence but not the outcome the model predicts, so the modeling contribution remains a well-specified hypothesis and a mechanism rather than a measurement. The next section says plainly what would turn it into one.

4.5 The test this paper invites

Three extensions would sharpen the framework, and the first matters most. The empirical section took the first of the model's two premises to real cities and found it holds; it did not take the outcome there, and that is the step that would convert a mechanism into a measurement. It requires a sample of cities for which three things can be measured: the configuration of the actual green network as patch geometry, connectivity, and redundancy; exposure to heat and drought, separated into years in which each acts alone and years in which they coincide; and an outcome the model predicts, of which the depth of decline and time to recovery in vegetation response after a stress event is the most tractable at scale, since it maps onto the health index and its recovery. The test is whether the observed response to co-occurring heat and drought exceeds the sum of the responses to each alone, and whether that excess depends on configuration as the model predicts. A positive answer would establish super-additivity in observation rather than assumption; a negative one would corroborate the additive finding already reported in this journal on synthetic data [12]. Such a design would also answer a limitation urban climate modeling has flagged against itself, that models validated on European cities carry uncertain validity elsewhere [11], since a sample weighted toward Asian and global South cities would test the mechanism where the urban-ecology literature has long noted its own thin coverage [71,72].

The second extension is early-warning indicators for the collapse the model produces, since the lagged, threshold dynamics suggest it may be detectable before it completes and the statistical theory of critical transitions offers candidate signatures that spatially explicit monitoring could look for [21,23,42,73]. The third is coupling the ecological network to the governance processes that shape it, closing the loop between how a city decides and how its ecosystems fare [16,68,74]. Widening the geography of such work beyond the global North, and taking the provisioning dimensions of urban green space seriously, would ground the framework in the diversity of actual urbanization [71,72,75,76]. How far standard ecological theory reaches into urban systems remains the productive tension in which such work proceeds [19,77,78,79].

5. Conclusions

Urban biodiversity is usually assessed as if the city faced one pressure at a time, and climate uncertainty is usually decomposed as if its sources were separable and additive. Cities face several pressures at once, and this paper has asked how the spatial configuration of a city's green infrastructure governs the fate of its biodiversity and ecosystem services under that condition. The first half of the answer is empirical. Across the 871 cities disclosing a hazard to CDP in 2021, the mean city names 3.60 of ten families and two thirds name three or more, and heat and water scarcity are named together by a third against 27.2 percent under independence, a lift of 1.24 that survives a fixed-margins null at z equal to 4.7. That dependence runs along regime lines rather than across the board, which motivates the pair the model compounds and rules out the assumption that every pair of urban stressors does so. The second half is the model. Using a spatially explicit patch-network metacommunity that holds total green area constant, we found that co-occurring stressors, when allowed to interact super-additively at a strength consistent with the compound-event literature, remove about a third more ecosystem health than their separate effects would sum to; that configuration is a second-order concern under single stressors but a first-order determinant under full polyuncertainty, with a fragmented network falling to a health index of 0.29 and a mean occupancy of 0.08 while a connected and redundant network of identical green area holds 0.53 and 0.45; and that where green is added matters more than how much, since corridors and distributed pocket parks raise the fragmented city to 0.57 and 0.61 while enlarging its isolated parks raises it only to 0.34. The first of these follows from an assumed interaction and the second is emergent, and it is the second that carries the paper's contribution.

Three things follow. First, assessment that evaluates pressures one at a time is systematically optimistic, and its optimism grows as the climate makes co-occurrence more likely, so the reform is to test combinations rather than refine each pressure in isolation. Second, urban ecological resilience can be given concrete structural content, the connectivity and redundancy of the green network, which makes it a property a city can build rather than an aspiration it can state. Third, the lever that does most of the work under compounding stress is arrangement rather than quantity, which inverts a common heuristic and points a fixed budget toward corridors and a distributed fabric of small patches.

The framework is falsifiable in principle, since it predicts a network advantage that widens with the number of co-occurring stressors, appears with a lag, and favors connectivity over quantity only under compounding, and testing it against real patch-network and vegetation-response data is the natural next step. The premise that stressors arrive together is now measured, through what cities disclose, rather than assumed, and it holds. That they compound super-additively, and that configuration decides what survives when they do, remain the behavior of a transparent model rather than evidence about any city, and should be read that way until the outcome side is measured too. The polyuncertainty a city cannot prevent, it can still prepare for, and the preparation is written into the shape of its green network.

Acknowledgments

Generative artificial intelligence was used in the preparation of this manuscript. Claude Opus 5 assisted with table design, with figure design, with converting the author's verified reference registry into the reference style of this journal, and with preparing the figure and verification scripts. It was not used to generate data, to produce or interpret results, or to select references. Every reference is drawn from a corpus assembled and verified by the author, every quantity reported is produced by the accompanying code from a fixed seed, and the author reviewed and verified all content and takes full responsibility for it.

References

1. Leonard M, Westra S, Phatak A, Lambert M, van den Hurk B, McInnes K, et al. A compound event framework for understanding extreme impacts. WIREs Clim Change. 2014;5(1): 113-128. doi: 10.1002/wcc.252
2. Zscheischler J, Westra S, van den Hurk BJJM, Seneviratne SI, Ward PJ, Pitman A, et al. Future climate risk from compound events. Nat Clim Chang. 2018;8(6): 469-477. doi: 10.1038/s41558-018-0156-3
3. Zscheischler J, Seneviratne SI. Dependence of drivers affects risks associated with compound events. Sci Adv. 2017;3(6): e1700263. doi: 10.1126/sciadv.1700263
4. Zscheischler J, Martius O, Westra S, Bevacqua E, Raymond C, Horton RM, et al. A typology of compound weather and climate events. Nat Rev Earth Environ. 2020;1(7): 333-347. doi: 10.1038/s43017-020-0060-z
5. Seneviratne SI, Zhang X, Adnan M, Badi W, Dereczynski C, Di Luca A, et al. Weather and climate extreme events in a changing climate. In: Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2021. Chapter 11. Available from: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter11.pdf
6. Field CB, Barros V, Stocker TF, Dahe Q, editors. Managing the risks of extreme events and disasters to advance climate change adaptation: a special report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2012. doi: 10.1017/CBO9781139177245

7. Seneviratne SI, Nicholls N, Easterling D, Goodess CM, Kanae S, Kossin J, et al. Changes in climate extremes and their impacts on the natural physical environment. In: Managing the risks of extreme events and disasters to advance climate change adaptation. Cambridge: Cambridge University Press; 2012. pp. 109-230. doi: 10.1017/CBO9781139177245.006

8. Brett L, White CJ, Domeisen DIV, van den Hurk B, Ward P, Zscheischler J. Review article: the growth in compound weather and climate event research in the decade since SREX. Nat Hazards Earth Syst Sci. 2025;25(8): 2591-2611. doi: 10.5194/nhess-25-2591-2025

9. Douville H. Doing better rather than promising more: a basic principle applicable to both climate modelling and climate policies. PLOS Clim. 2025;4(1): e0000466. doi: 10.1371/journal.pclm.0000466

10. Douville H. All climate models are wrong but wrong models are useful: why, where, and how? PLOS Clim. 2026;5(7): e0001000. doi: 10.1371/journal.pclm.0001000

11. Kermarrec G, Montillet J-P, Li D. Uncertainty in urban climate modeling: bridging the gap between science and policy. PLOS Clim. 2025;4(10): e0000743. doi: 10.1371/journal.pclm.0000743

12. Katende R. Bridging the macro-micro divide through a new paradigm for climate resilience assessment in data-scarce regions. PLOS Clim. 2026;5(1): e0000662. doi: 10.1371/journal.pclm.0000662

13. Jain A, Walsh E, Lal A. Communicating uncertainty to policy makers in maps: a systematic scoping review of meaningful to misleading current practice. PLOS Clim. 2026;5(7): e0000707. doi: 10.1371/journal.pclm.0000707

14. Collins JP, Kinzig A, Grimm NB, Fagan WF, Hope D, Wu J, et al. A new urban ecology. Am Sci. 2000;88: 416-425. doi: 10.1511/2000.35.416

15. Pickett STA, Cadenasso ML, Grove JM, Groffman PM, Band LE, Boone CG, et al. Beyond urban legends: an emerging framework of urban ecology, as illustrated by the Baltimore Ecosystem Study. Bioscience. 2008;58(2): 139-150. doi: 10.1641/B580208

16. McPhearson T, Pickett STA, Grimm NB, Niemela J, Alberti M, Elmqvist T, et al. Advancing urban ecology toward a science of cities. Bioscience. 2016;66(3): 198-212. doi: 10.1093/biosci/biw002

17. Johnson PTJ, Hoverman JT, McKenzie VJ, Blaustein AR, Richgels KLD. Urbanization and wetland communities: applying metacommunity theory to understand the local and landscape effects. J Appl Ecol. 2013;50(1): 34-42. doi: 10.1111/1365-2664.12022

18. Gallo T, Fidino M, Lehrer EW, Magle SB. Mammal diversity and metacommunity dynamics in urban green spaces: implications for urban wildlife conservation. Ecol Appl. 2017;27(8): 2330-2341. doi: 10.1002/eap.1611

19. Stukenholtz EE, Stevens RD. Taxonomic and functional components of avian metacommunity structure along an urban gradient. PLoS One. 2022;17(8): e0271405. doi: 10.1371/journal.pone.0271405

20. Almeida-Gomes M, Valente-Neto F, Pacheco EO, Ganci CC, Leibold MA, Melo AS, et al. How does the landscape affect metacommunity structure? A quantitative review for lentic environments. Curr Landsc Ecol Rep. 2020;5(3): 68-75. doi: 10.1007/s40823-020-00049-6

21. Chen X, Zhao Y, Zhou C, Cai Y. Nonlinear impact of population shrinkage on urban ecological resilience: a threshold effect analysis based on city-level panel data from the Yangtze River Economic Belt, China. Land. 2026;15(2): 261. doi: 10.3390/land15020261

22. Hu Y, Zhang J, Wang C, Ma Y, Feng X, Fu B. Daily ecological resilience dynamics under multiple hazards for spatially explicit ecological intervention strategies: insights from Beijing's 2023 extreme rainfall event. Landsc Ecol. 2026;41(2): 29. doi: 10.1007/s10980-025-02292-w
23. Hu W. Dynamic evolution of urban landscape spatial pattern and evaluation of ecological vulnerability. Int J Image Data Fusion. 2026;17(1): 2613391. doi: 10.1080/19479832.2026.2613391
24. Sharifi A. Resilient urban forms: a macro-scale analysis. Cities. 2019;85: 1-14. doi: 10.1016/j.cities.2018.11.023
25. Leibold MA, Holyoak M, Mouquet N, Amarasekare P, Chase JM, Hoopes MF, et al. The metacommunity concept: a framework for multi-scale community ecology. Ecol Lett. 2004;7(7): 601-613. doi: 10.1111/j.1461-0248.2004.00608.x
26. CDP. 2021 Cities Climate Hazards [dataset]. London: CDP Open Data Portal; 2021. Resource ht3d-86mm. Available from: https://data.cdp.net/Climate-Hazards/2021-Cities-Climate-Hazards/ht3d-86mm
27. MacGregor-Fors I, Rega-Brodsky CC, Kotze DJ, MacIvor JS, Hahs AK, Moretti M, et al. Navigating urban ecology: conceptual and methodological insights. Ecology. 2026;107(6): e70402. doi: 10.1002/ecy.70402
28. Niemela J. Is there a need for a theory of urban ecology? Urban Ecosyst. 1999;3: 57-65. doi: 10.1023/A:1009595932440
29. Sexton AN, Egerer M. Re-thinking the urban biotic homogenization hypothesis. Ecol Lett. 2026;29(2): e70342. doi: 10.1111/ele.70342

30. Ramalho CE, Hobbs RJ. Time for a change: dynamic urban ecology. Trends Ecol Evol. 2012;27(3): 179-188. doi: 10.1016/j.tree.2011.10.008

31. Lokatis S, Jeschke JM, Bernard-Verdier M, Buchholz S, Grossart H-P, Havemann F, et al. Hypotheses in urban ecology: building a common knowledge base. Biol Rev. 2023;98(5): 1530-1547. doi: 10.1111/brv.12964

32. Walker WE, Harremoes P, Rotmans J, van der Sluijs JP, van Asselt MBA, Janssen P, et al. Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support. Integr Assess. 2003;4(1): 5-17. doi: 10.1076/iaij.4.1.5.16466

33. Lempert RJ, Popper SW, Bankes SC. Shaping the next one hundred years: new methods for quantitative, long-term policy analysis. Santa Monica: RAND Corporation; 2003. Available from: https://www.rand.org/pubs/monograph_reports/MR1626.html

34. Marchau VAWJ, Walker WE, Bloemen PJTM, Popper SW, editors. Decision making under deep uncertainty: from theory to practice. Cham: Springer; 2019. doi: 10.1007/978-3-030-05252-2

35. Alberti M, Palkovacs EP, Des Roches S, De Meester L, Brans KI, Govaert L, et al. The complexity of urban eco-evolutionary dynamics. Bioscience. 2020;70(9): 772-793. doi: 10.1093/biosci/biaa079

36. Pickett STA, Cadenasso ML, Grove JM. Resilient cities: meaning, models, and metaphor for integrating the ecological, socio-economic, and planning realms. Landsc Urban Plan. 2004;69(4): 369-384. doi: 10.1016/j.landurbplan.2003.10.035

37. Heino J. The importance of metacommunity ecology for environmental assessment research in the freshwater realm. Biol Rev. 2013;88(1): 166-178. doi: 10.1111/j.1469-185X.2012.00244.x

38. Hager GW, Belt KT, Stack W, Burgess K, Grove JM, Caplan B, et al. Socioecological revitalization of an urban watershed. Front Ecol Environ. 2013;11(1): 28-36. doi: 10.1890/120069

39. Breuste J, Qureshi S, Li J. Applied urban ecology for sustainable urban environment. Urban Ecosyst. 2013;16(4): 675-680. doi: 10.1007/s11252-013-0337-9

40. Baede APM, Ahlonsou E, Ding Y, Schimel D. The climate system: an overview. In: Climate change 2001: the scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2001. pp. 85-98. Available from: https://www.ipcc.ch/site/assets/uploads/2018/03/TAR-01.pdf

41. McGrath B, Pickett STA. The metacity: a conceptual framework for integrating ecology and urban design. Challenges. 2011;2(4): 55-72. doi: 10.3390/challe2040055

42. Scheffer M, Bascompte J, Brock WA, Brovkin V, Carpenter SR, Dakos V, et al. Early-warning signals for critical transitions. Nature. 2009;461(7260): 53-59. doi: 10.1038/nature08227

43. Parris KM. Existing ecological theory applies to urban environments. Landsc Ecol Eng. 2018;14(2): 201-208. doi: 10.1007/s11355-018-0351-4

44. Almulhim AI, Cobbinah PB. On urban sustainability: urbanization and climate change collision. Sustain Dev. 2026;34(S2): 979-995. doi: 10.1002/sd.70382

45. Eyring V, Gillett NP, Achuta Rao KM, Barimalala R, Barreiro Parrillo M, Bellouin N, et al. Human influence on the climate system. In: Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the

Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2021. pp. 423-552. doi: 10.1017/9781009157896.005

46. Sharifi A, Yamagata Y. Resilient urban planning: major principles and criteria. Energy Procedia. 2014;61: 1491-1495. doi: 10.1016/j.egypro.2014.12.154
47. Desouza KC, Flanery TH. Designing, planning, and managing resilient cities: a conceptual framework. Cities. 2013;35: 89-99. doi: 10.1016/j.cities.2013.06.003
48. Haasnoot M, Kwakkel JH, Walker WE, ter Maat J. Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. Glob Environ Change. 2013;23(2): 485-498. doi: 10.1016/j.gloenvcha.2012.12.006
49. Callahan CW. Present and future limits to climate change adaptation. Nat Sustain. 2025;8: 336-342. doi: 10.1038/s41893-025-01519-7
50. Kalra N, Hallegatte S, Lempert R, Brown C, Fozzard A, Gill S, et al. Agreeing on robust decisions: new processes for decision making under deep uncertainty. Policy Research Working Paper 6906. Washington, DC: World Bank; 2014. doi: 10.1596/1813-9450-6906
51. Bonjean Stanton MC, Roelich K. Decision making under deep uncertainties: a review of the applicability of methods in practice. Technol Forecast Soc Change. 2021;171: 120939. doi: 10.1016/j.techfore.2021.120939
52. Vale LJ. The politics of resilient cities: whose resilience and whose city? Build Res Inf. 2014;42(2): 191-201. doi: 10.1080/09613218.2014.850602
53. Zahnow R, Rad Yousefnia A, Hassankhani M, Cheshmehzangi A. Climate change inequalities: a systematic review of disparities in access to mitigation and adaptation measures. Environ Sci Policy. 2025;165: 104021. doi: 10.1016/j.envsci.2025.104021

54. Pizzo B. Problematizing resilience: implications for planning theory and practice. Cities. 2015;43: 133-140. doi: 10.1016/j.cities.2014.11.015

55. Pickett STA, McGrath B, Cadenasso ML, Felson AJ. Ecological resilience and resilient cities. Build Res Inf. 2014;42(2): 143-157. doi: 10.1080/09613218.2014.850600

56. Rus K, Kilar V, Koren D. Resilience assessment of complex urban systems to natural disasters: a new literature review. Int J Disaster Risk Reduct. 2018;31: 311-330. doi: 10.1016/j.ijdrr.2018.05.015

57. Zhang X, Li H. Urban resilience and urban sustainability: what we know and what we do not know? Cities. 2018;72: 141-148. doi: 10.1016/j.cities.2017.08.009

58. Chelleri L, Baravikova A. Understandings of urban resilience meanings and principles across Europe. Cities. 2021;108: 102985. doi: 10.1016/j.cities.2020.102985

59. Chapagain PS, Banskota TR, Shrestha S, Khanal NR, Yili Z, Yan J, et al. Studies on adaptive capacity to climate change: a synthesis of changing concepts, dimensions, and indicators. Humanit Soc Sci Commun. 2025;12: 331. doi: 10.1057/s41599-025-04453-3

60. Urban MC, De Meester L, Vellend M, Stoks R, Vanoverbeke J. A crucial step toward realism: responses to climate change from an evolving metacommunity perspective. Evol Appl. 2012;5(2): 154-167. doi: 10.1111/j.1752-4571.2011.00208.x

61. Urban MC, Skelly DK. Evolving metacommunities: toward an evolutionary perspective on metacommunities. Ecology. 2006;87(7): 1616-1626. doi: 10.1890/0012-9658(2006)87[1616:EMTAEP]2.0.CO;2

62. Birkmann J, Garschagen M, Kraas F, Quang N. Adaptive urban governance: new challenges for the second generation of urban adaptation strategies to climate change. Sustain Sci. 2010;5(2): 185-206. doi: 10.1007/s11625-010-0111-3

63. da Cruz NF, Rode P, McQuarrie M. New urban governance: a review of current themes and future priorities. J Urban Aff. 2019;41(1): 1-19. doi: 10.1080/07352166.2018.1499416

64. Mitchell D, Enemark S, van der Molen P. Climate resilient urban development: why responsible land governance is important. Land Use Policy. 2015;48: 190-198. doi: 10.1016/j.landusepol.2015.05.026

65. Huang C-W, McDonald RI, Seto KC. The importance of land governance for biodiversity conservation in an era of global urban expansion. Landsc Urban Plan. 2018;173: 44-50. doi: 10.1016/j.landurbplan.2018.01.011

66. Goh K. Planet at the end of the city: how climate changes the nature of urban theory. Int J Urban Reg Res. 2026;50(2): 240-255. doi: 10.1111/1468-2427.70010

67. Marques LP, Collevatti RG. Low interaction in an interdisciplinary research field: a scientometric view of 80 years of publication in urban ecology. Urban Ecosyst. 2026;29: 39. doi: 10.1007/s11252-026-01900-0

68. Pickett STA, Cadenasso ML, Childers DL, McDonnell MJ, Zhou W. Evolution and future of urban ecological science: ecology in, of, and for the city. Ecosyst Health Sustain. 2016;2(7): e01229. doi: 10.1002/ehs2.1229

69. Pickett STA, Cadenasso ML, Rademacher AM. Toward pluralizing ecology: finding common ground across sociocultural and scientific perspectives. Ecosphere. 2022;13(9): e4231. doi: 10.1002/ecs2.4231

70. Mugerauer R. Toward a theory of integrated urban ecology: complementing Pickett et al. Ecol Soc. 2010;15(4): 31. doi: 10.5751/ES-03667-150431

71. McHale MR, Bunn DN, Pickett STA, Twine W. Urban ecology in a developing world: why advanced socioecological theory needs Africa. Front Ecol Environ. 2013;11(10): 556-564. doi: 10.1890/120157

72. Noxolo BM, Kanosvamhira TP. Assessing the viability of hydroponics for low-income farmers in South Africa's urban agriculture sector: an urban political ecology perspective. Urban Agric Reg Food Syst. 2026;11(1): e70036. doi: 10.1002/uar2.70036

73. Lu Z, Zhang S, Yu X, Fu Y. Spatio-temporal evolution and influencing factors of ecological resilience in the Yellow River Basin. Front Environ Sci. 2026;14: 1778474. doi: 10.3389/fenvs.2026.1778474

74. Pickett STA, Zhou W. Global urbanization as a shifting context for applying ecological science toward the sustainable city. Ecosyst Health Sustain. 2015;1(1): 1-15. doi: 10.1890/EHS14-0014.1

75. Cox S. Climate change and the limits of urban thought. Dialogues Urban Res. 2026. doi: 10.1177/27541258251410151

76. Walls W, Greene B. Ecological design and climate change in Melbourne: impacts on the Birrarung's bank. Landsc Res. 2026:1-17. doi: 10.1080/01426397.2025.2610277

77. Rebele F. Urban ecology and special features of urban ecosystems. Glob Ecol Biogeogr Lett. 1994;4(6): 173-187. doi: 10.2307/2997649

78. Forman RTT. Urban ecology principles: are urban ecology and natural area ecology really different? Landsc Ecol. 2016;31(8): 1653-1662. doi: 10.1007/s10980-016-0424-4

79. Pickett STA, Cadenasso ML. How many principles of urban ecology are there? Landsc Ecol. 2017;32(4): 699-705. doi: 10.1007/s10980-017-0492-0

Supporting information

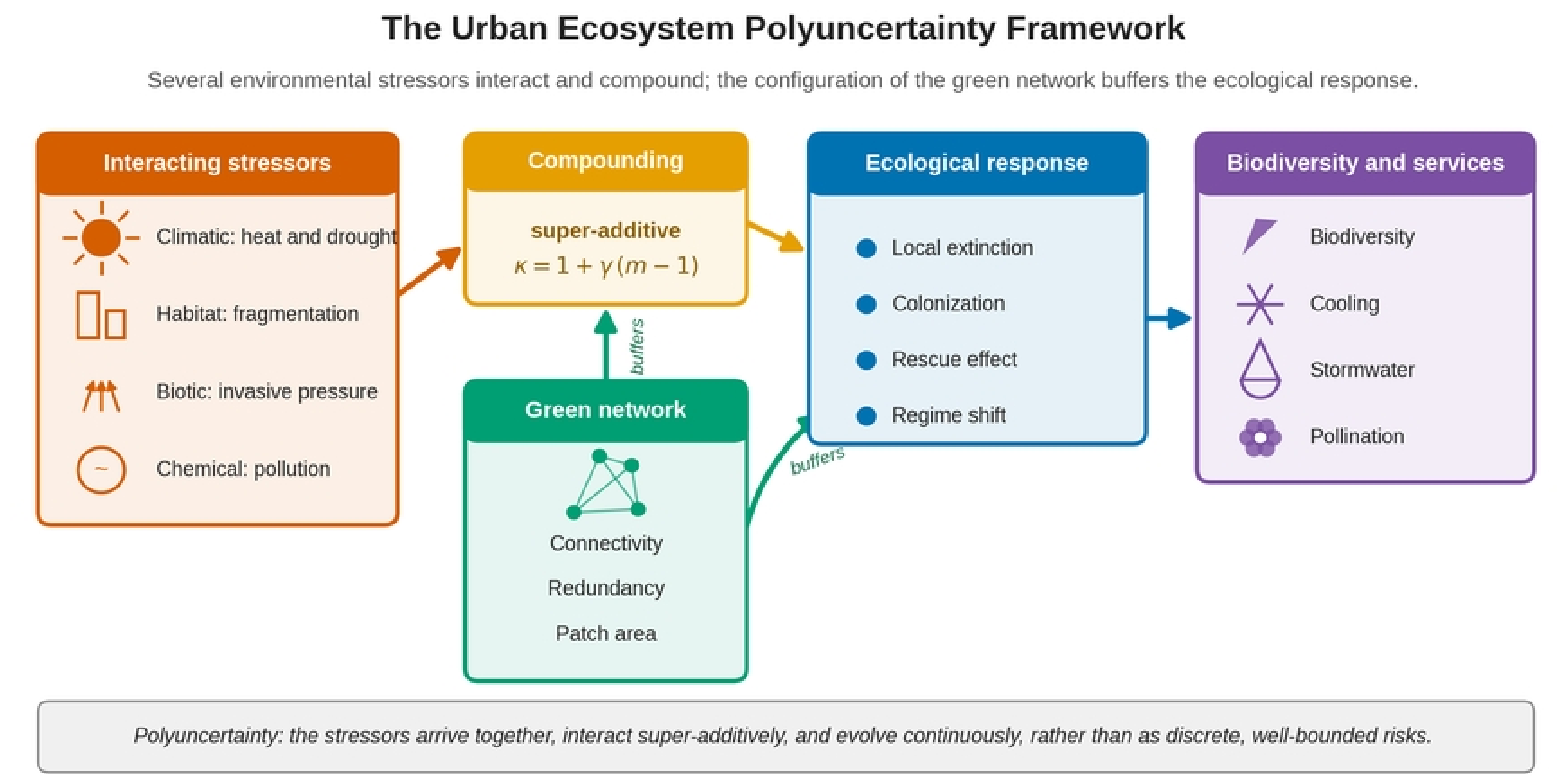
S1 Appendix. Reduced ODD protocol for the urban green-network model. Purpose, entities, state variables and scales, process overview and scheduling, design concepts, initialization, input data, and submodels, stated against the standard template for describing individual and agent-based models.

S2 Appendix. Full model specification, parameter values, and source code. The complete parameter set, the disturbance and drift submodels, and the self-contained Python script with its fixed random seed.

S3 Appendix. Co-occurrence analysis: data, code, and the full pairwise table. The extraction from the CDP 2021 climate hazard disclosure, the curveball randomization script with its fixed seed, and the observed lift, null mean, null 95 percent interval, standardized excess, and two-sided p value for all 45 family pairs, under both the all-named-hazards and the significant-impact definitions.

S1 Data. Numeric series behind every figure. A workbook containing the values plotted in Figs 5 through 10 and reported in Tables 1 through 6.

S2 Data. City-by-family incidence matrix and co-occurrence results. The binary incidence matrix analyzed in Section 3.1 and the machine-readable results file from which Fig 4 and Table 5 are drawn. The underlying disclosures are public and are redistributed under the terms of the CDP Open Data Portal.



The Urban Ecosystem Polyuncertainty Framework
Several environmental stressors interact and compound; the configuration of the green network buffers the ecological response.
Interacting stressors
Climatic: heat and drought
Habitat: fragmentation
Biotic: invasive pressure
Chemical: pollution
Compounding
super-additive
κ = 1 + γ (m − 1)
buffers
Green network
Connectivity
Redundancy
Patch area
buffers
Ecological response
Local extinction
Colonization
Rescue effect
Regime shift
Biodiversity and services
Biodiversity
Cooling
Stormwater
Pollination
Polyuncertainty: the stressors arrive together, interact super-additively, and evolve continuously, rather than as discrete, well-bounded risks.

Figure1

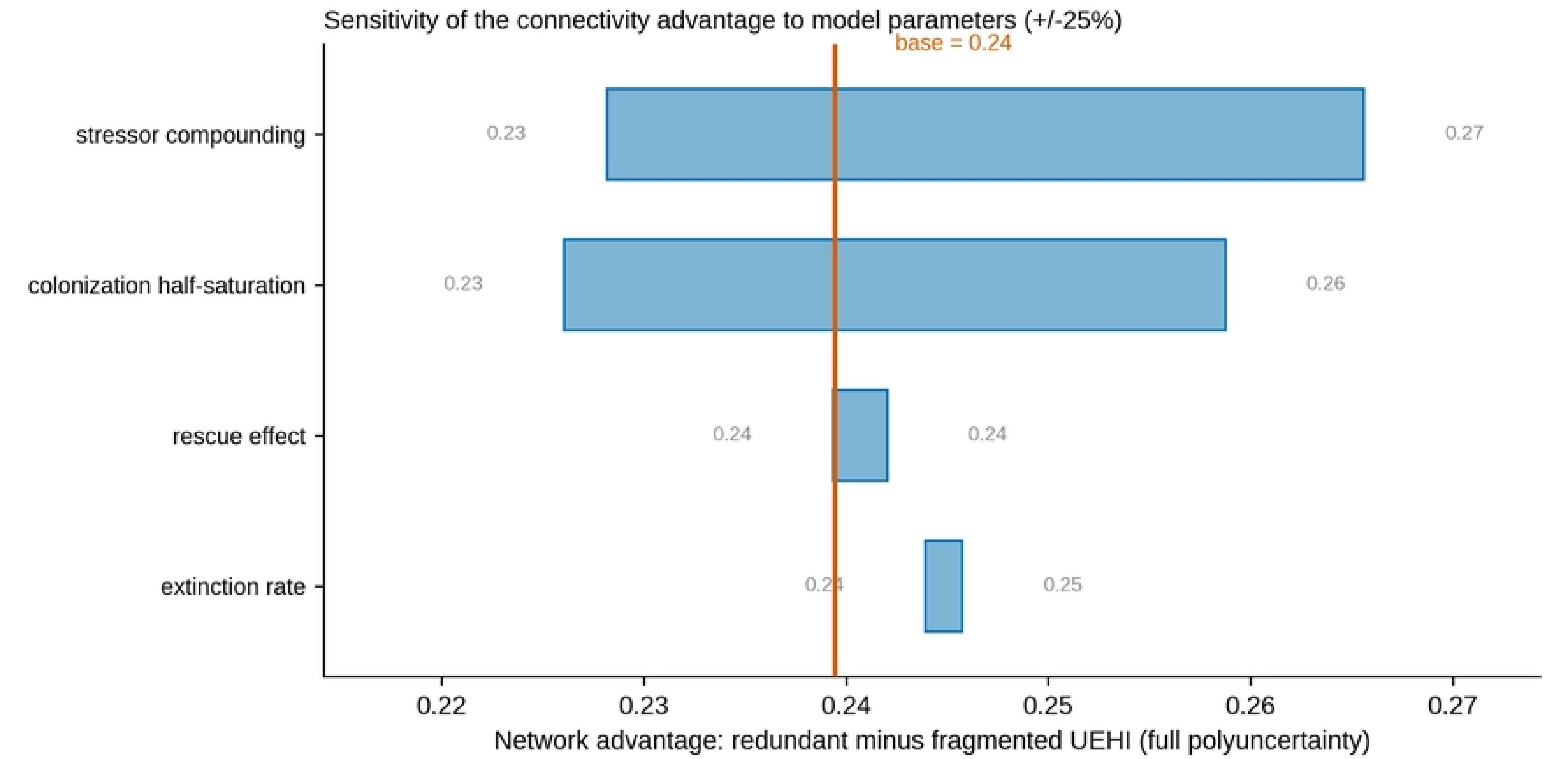

Sensitivity of the connectivity advantage to model parameters (+/-25%)
base = 0.24
stressor compounding
colonization half-saturation
rescue effect
extinction rate
0.23
0.27
0.23
0.26
0.24
0.24
0.24
0.25
0.22
0.23
0.24
0.25
0.26
0.27
Network advantage: redundant minus fragmented UEHI (full polyuncertainty)

Figure10

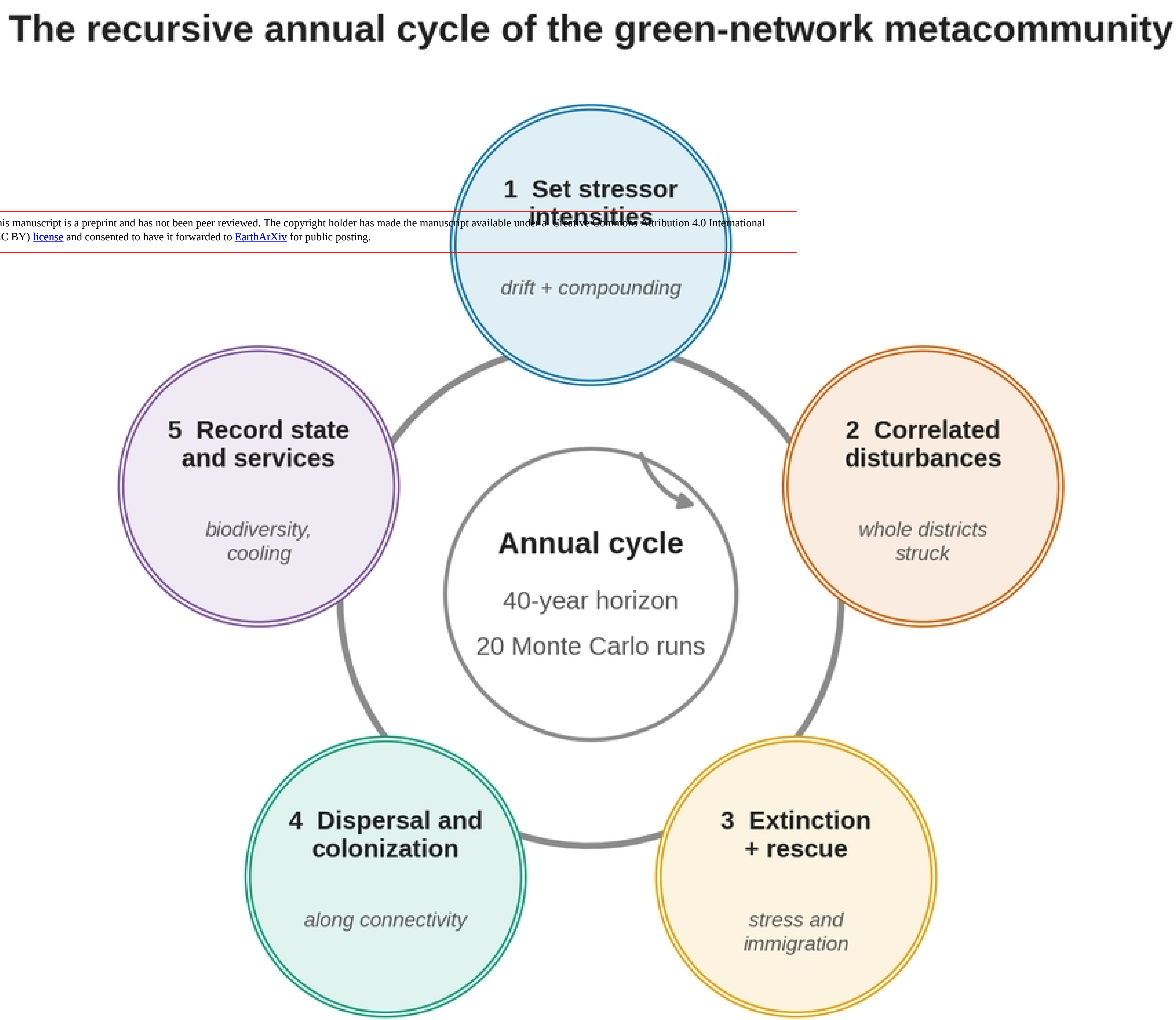

The recursive annual cycle of the green-network metacommunity
1 Set stressor intensities
drift + compounding
2 Correlated disturbances
whole districts struck
3 Extinction + rescue
stress and immigration
4 Dispersal and colonization
along connectivity
5 Record state and services
biodiversity, cooling
Annual cycle
40-year horizon
20 Monte Carlo runs

Figure2

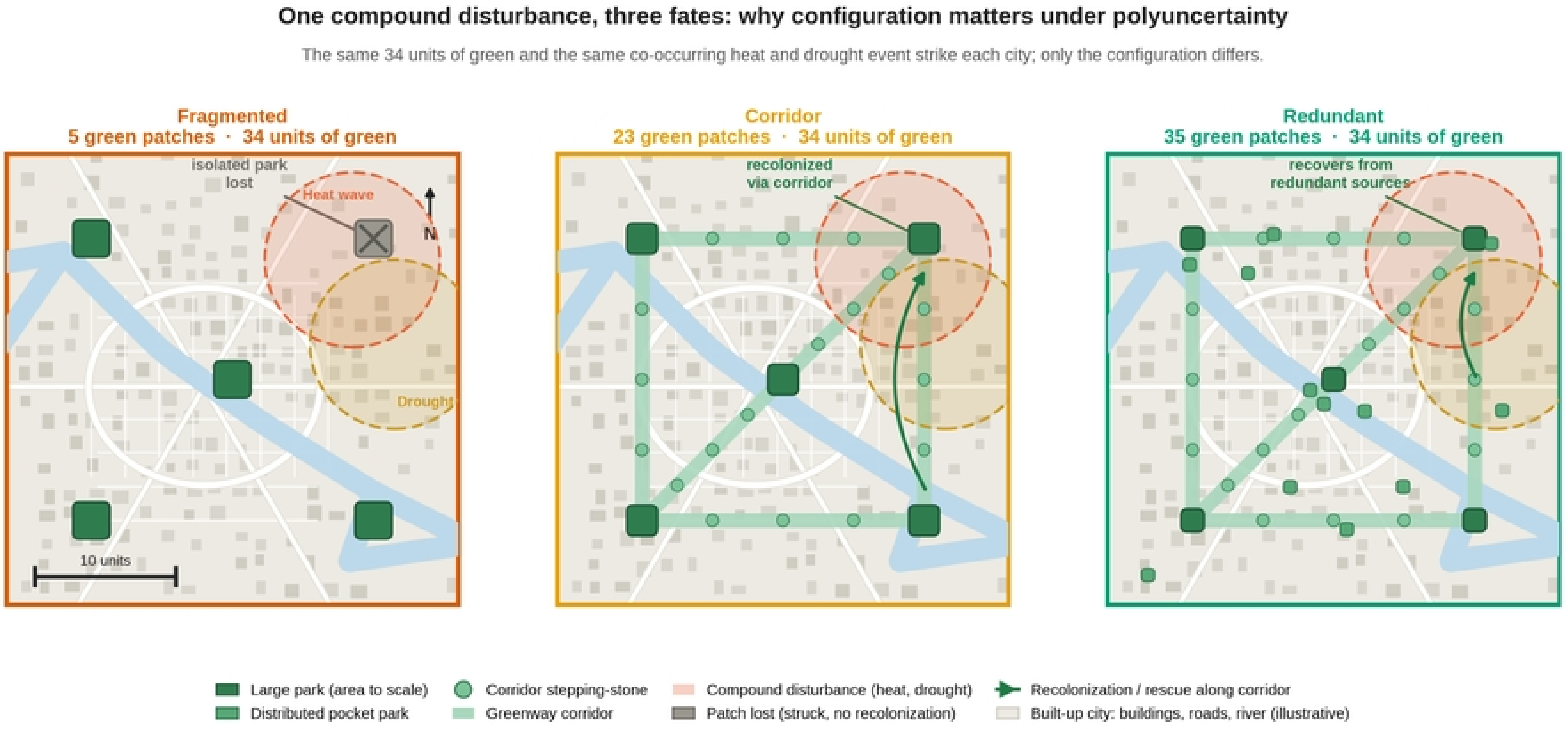
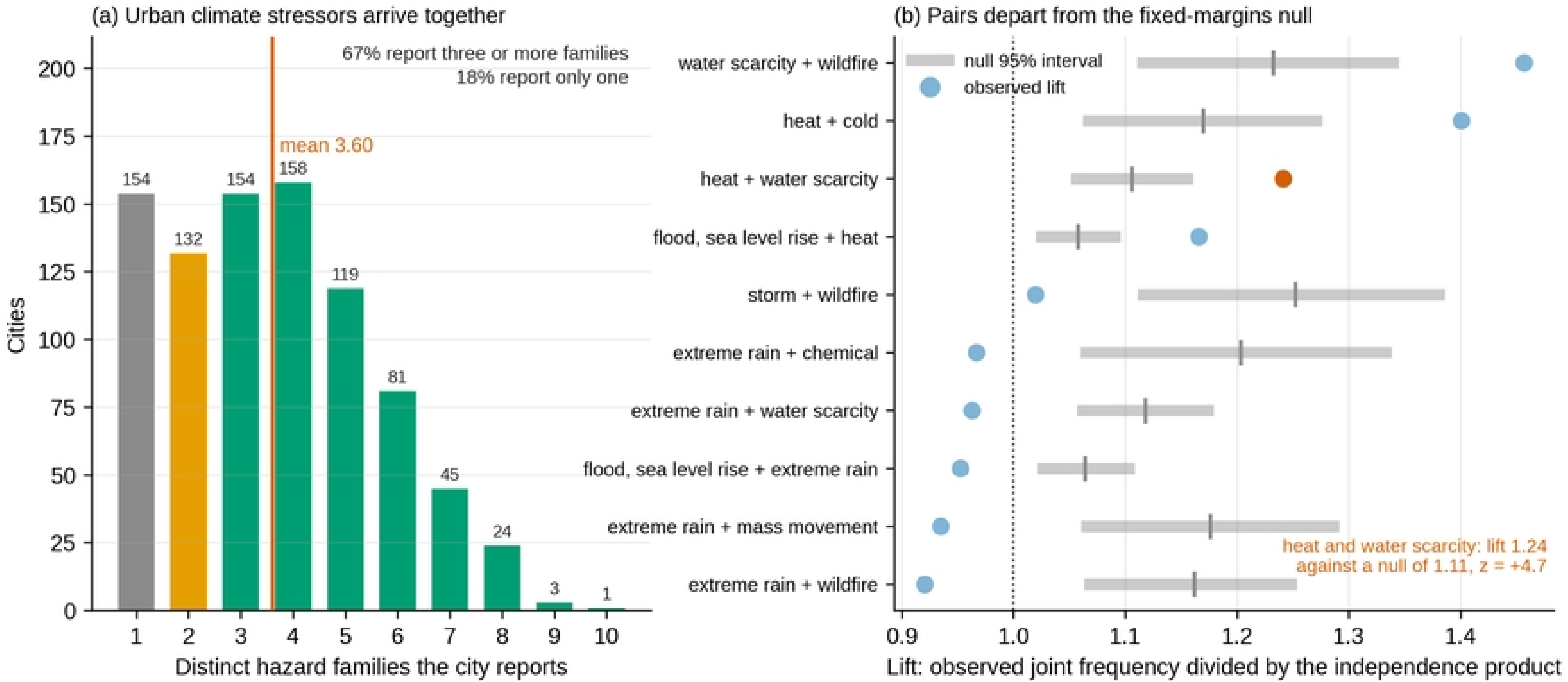
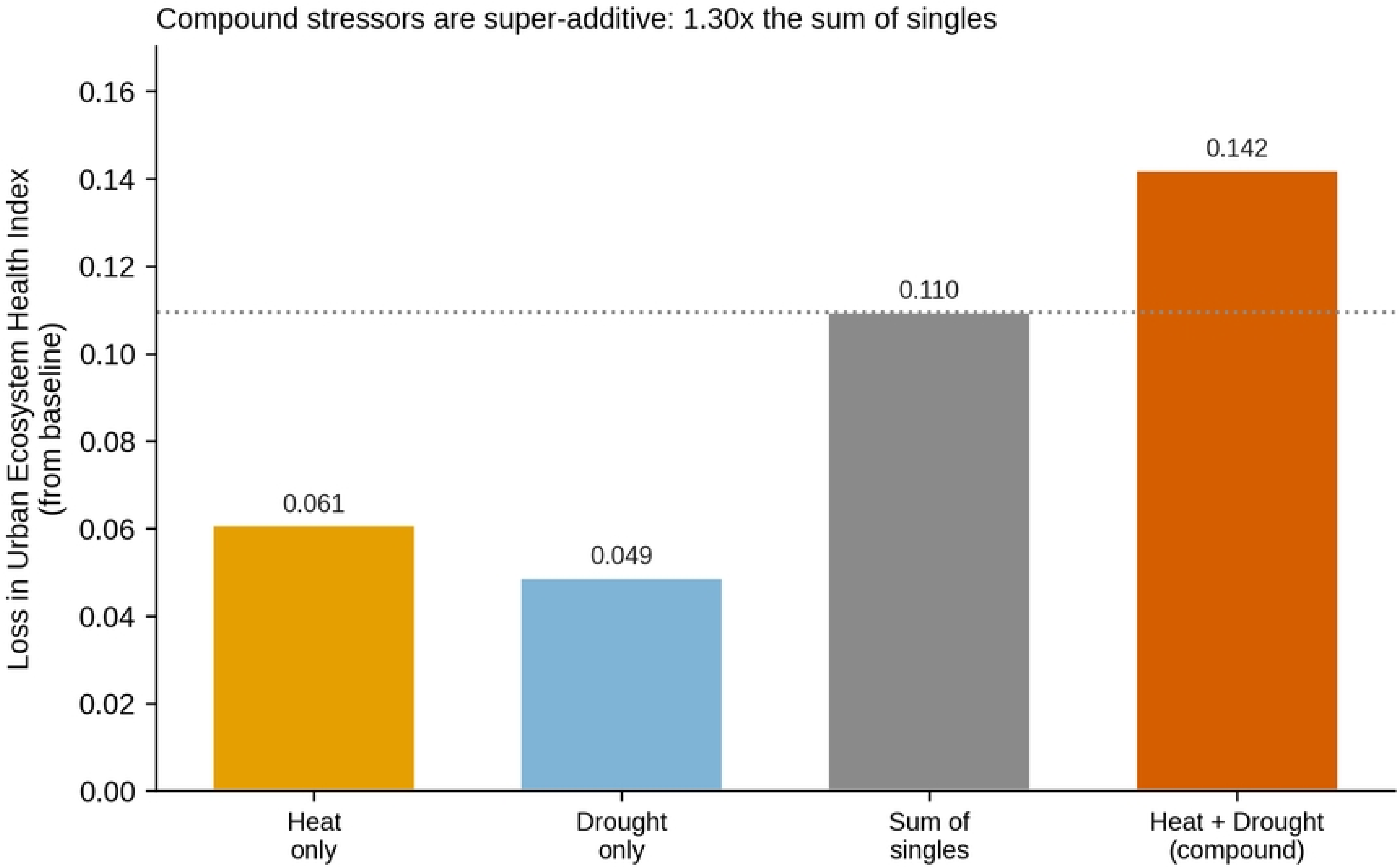

One compound disturbance, three fates: why configuration matters under polyuncertainty
The same 34 units of green and the same co-occurring heat and drought event strike each city; only the configuration differs.
Fragmented
5 green patches · 34 units of green
isolated park lost
Heat wave
Drought
N
10 units
Corridor
23 green patches · 34 units of green
recolonized via corridor
Redundant
35 green patches · 34 units of green
recovers from redundant sources
Large park (area to scale)
Distributed pocket park
Corridor stepping-stone
Greenway corridor
Compound disturbance (heat, drought)
Patch lost (struck, no recolonization)
Recolonization / rescue along corridor
Built-up city: buildings, roads, river (illustrative)

Figure3



(a) Urban climate stressors arrive together
67% report three or more families
18% report only one
mean 3.60
Cities
Distinct hazard families the city reports
154
132
154
158
119
81
45
24
3
1
(b) Pairs depart from the fixed-margins null
null 95% interval
observed lift
water scarcity + wildfire
heat + cold
heat + water scarcity
flood, sea level rise + heat
storm + wildfire
extreme rain + chemical
extreme rain + water scarcity
flood, sea level rise + extreme rain
extreme rain + mass movement
extreme rain + wildfire
heat and water scarcity: lift 1.24
against a null of 1.11, z = +4.7
Lift: observed joint frequency divided by the independence product

Figure4



Compound stressors are super-additive: 1.30x the sum of singles
Loss in Urban Ecosystem Health Index
(from baseline)
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.061
0.049
0.110
0.142
Heat
only
Drought
only
Sum of
singles
Heat + Drought
(compound)

Figure5

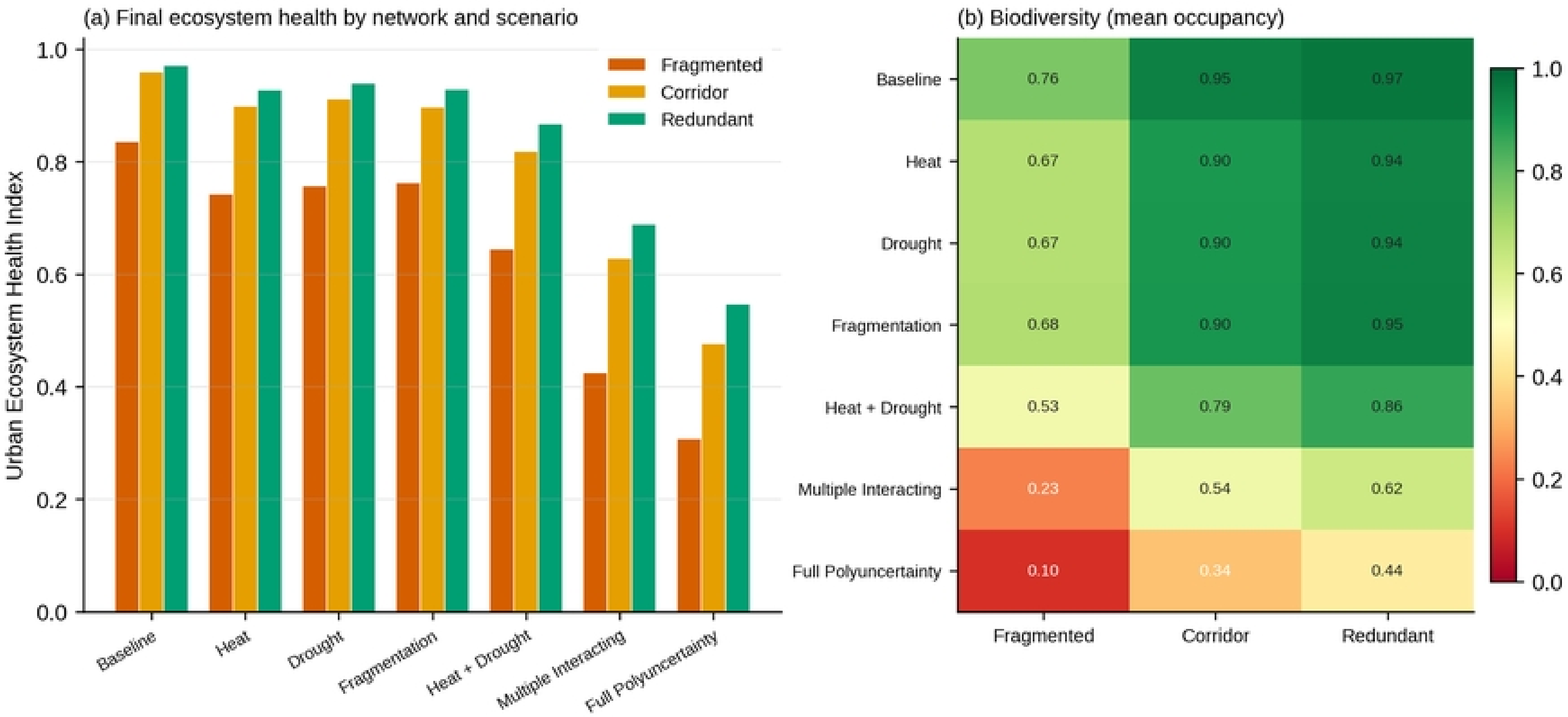
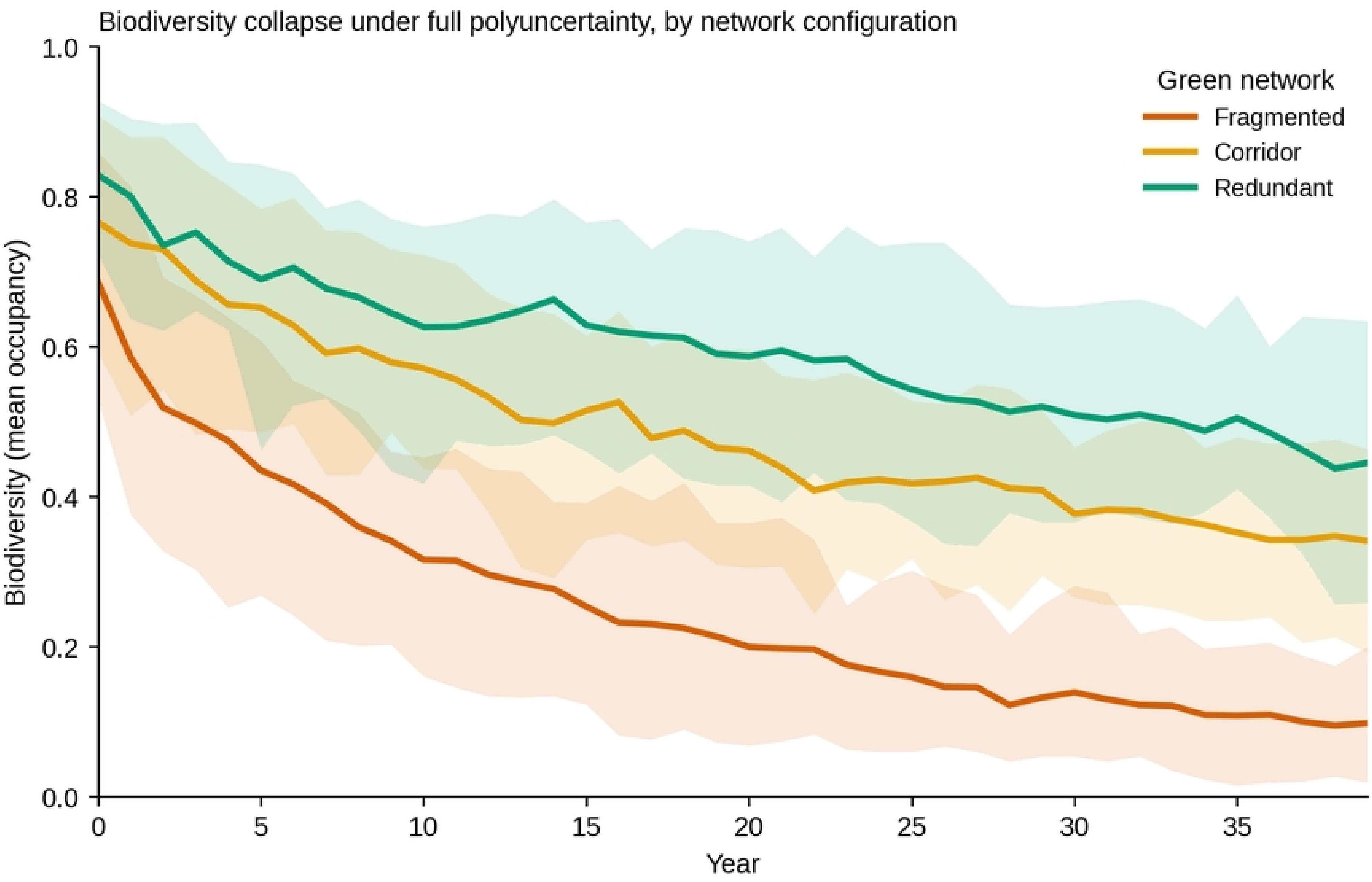

(a) Final ecosystem health by network and scenario
Urban Ecosystem Health Index
1.0
0.8
0.6
0.4
0.2
0.0
Fragmented
Corridor
Redundant
Baseline
Heat
Drought
Fragmentation
Heat + Drought
Multiple Interacting
Full Polyuncertainty
(b) Biodiversity (mean occupancy)
Baseline
Heat
Drought
Fragmentation
Heat + Drought
Multiple Interacting
Full Polyuncertainty
0.76
0.95
0.97
0.67
0.90
0.94
0.67
0.90
0.94
0.68
0.90
0.95
0.53
0.79
0.86
0.23
0.54
0.62
0.10
0.34
0.44
Fragmented
Corridor
Redundant
1.0
0.8
0.6
0.4
0.2
0.0

Figure6



Biodiversity collapse under full polyuncertainty, by network configuration
Green network
Fragmented
Corridor
Redundant
Biodiversity (mean occupancy)
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
35
Year

Figure7

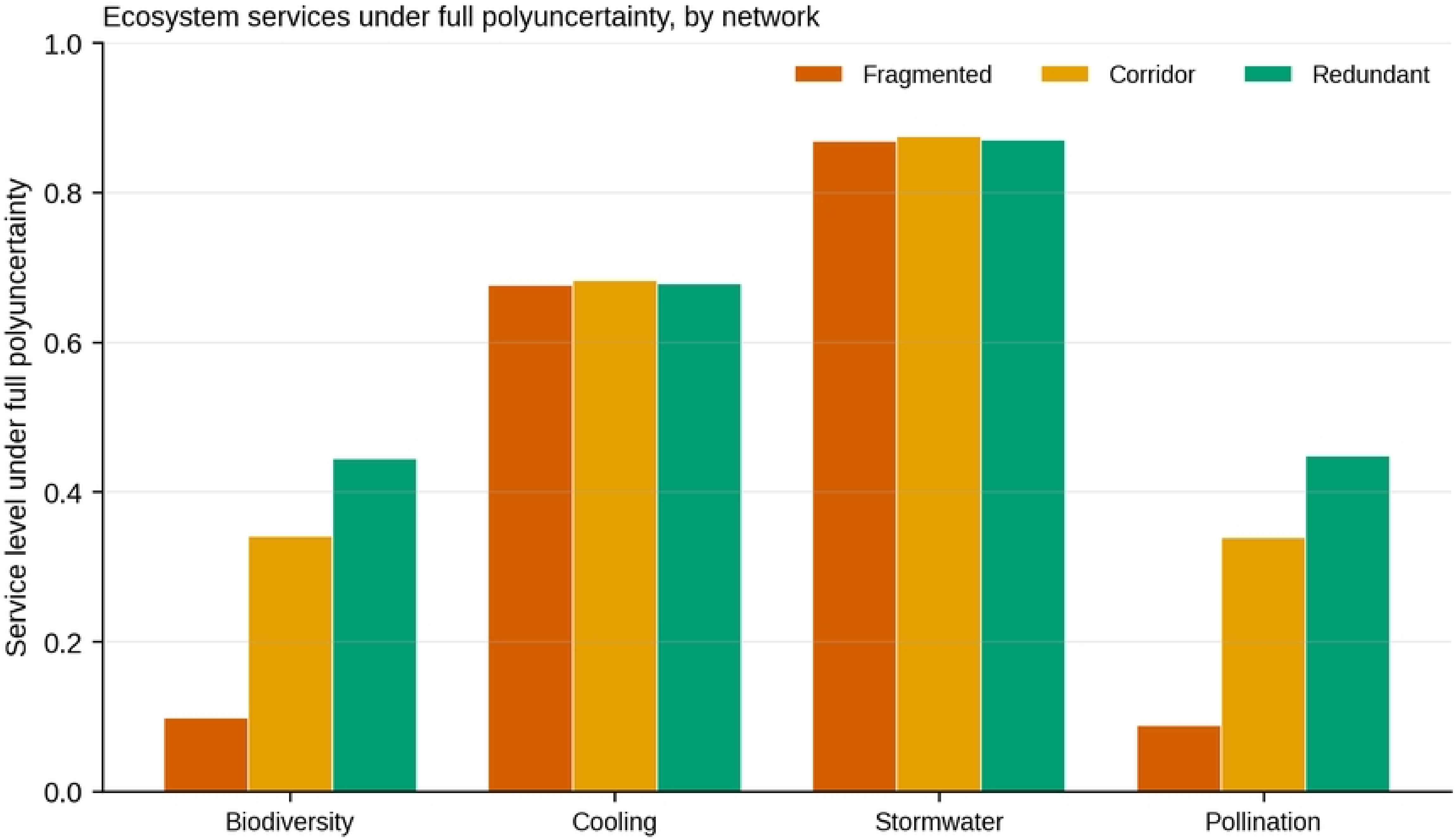

Ecosystem services under full polyuncertainty, by network
Fragmented
Corridor
Redundant
Service level under full polyuncertainty
1.0
0.8
0.6
0.4
0.2
0.0
Biodiversity
Cooling
Stormwater
Pollination

Figure8

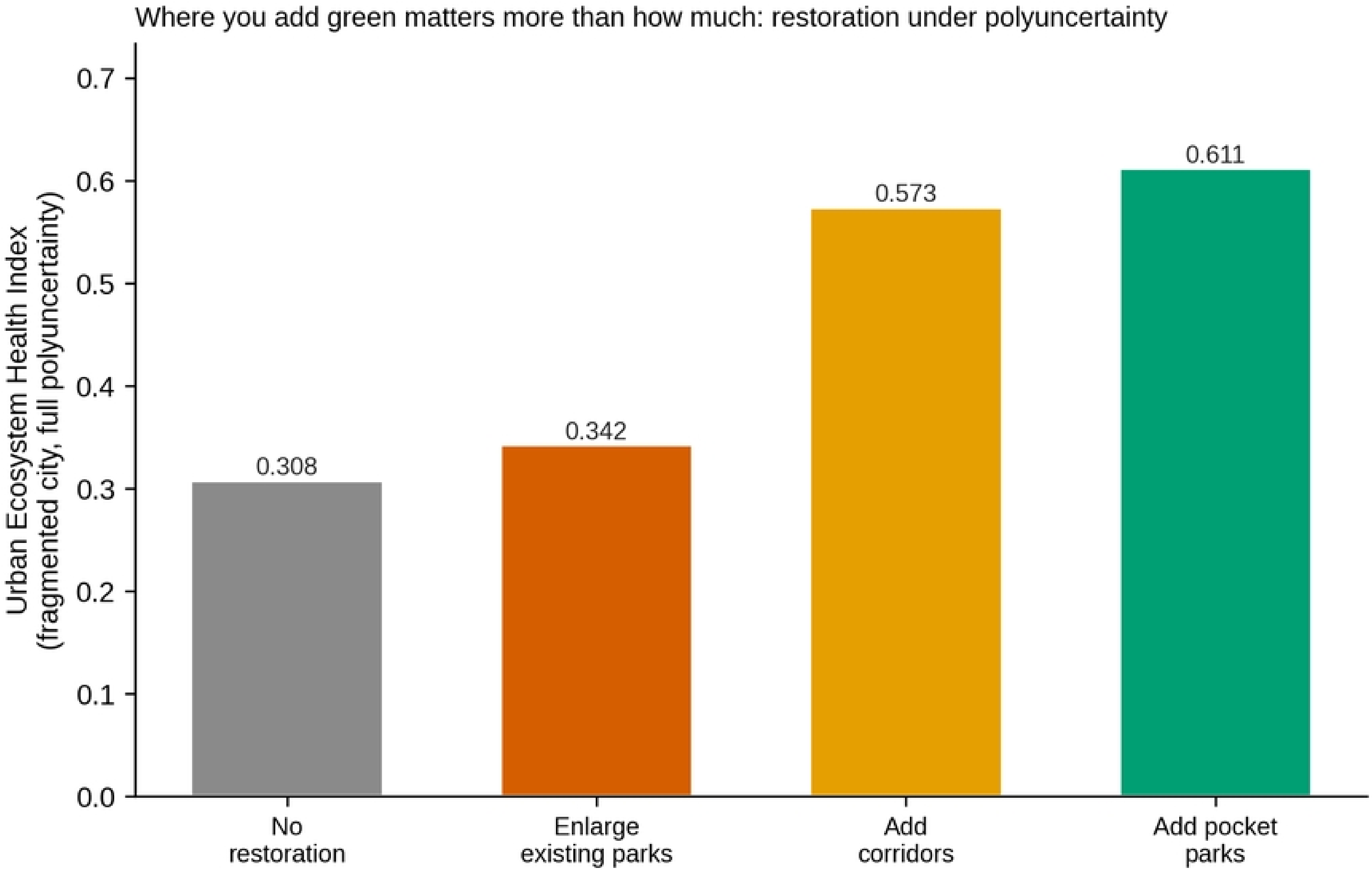

Where you add green matters more than how much: restoration under polyuncertainty
Urban Ecosystem Health Index
(fragmented city, full polyuncertainty)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.308
0.342
0.573
0.611
No
restoration
Enlarge
existing parks
Add
corridors
Add pocket
parks

Figure9