Ecography

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# Supplementary material

## Appendix 1

## Materials & Methods

We searched the literature for the term *extinction debt* isolated and in combinations with the following terms: *relaxation time*, *extinction dynamics, model*, *metapopulation*, *mechanistic model*, *individual-based model*, *agent-based model*, *biotic interactions*, *temporal*, *network stability, delayed extinction* and *prediction* in the Clarivate Analytics Web of Science collection, for works published between 2009 and 2017 (Fig. A1). Although it would strictly fall outside of this time window, Guardiola et al. (2018) has been included in this review because of its date of first publication (November 10th, 2017). Furthermore, because "relaxation time" is a concept closely linked to extinction debt, we extended the period of search to for this term to 1972, when it was first used in Ecology by Diamond (1972). We restricted our searches to the Environmental Sciences & Ecology research area of the Web of Science collection. In total, we found 397 studies. The 83 studies retained by filtering the through the 'empirical', 'theoretical' and 'methodological work' categories are listed in tables A1, A2, and A3, respectively. Additionally, List A1 lists the 31 papers arising from our search and appropriately cited in the main text, but not fitting the above categories.

To assess if and how much each study addressed the spatial-temporal dynamics and mechanisms behind extinction debt, we analyzed results from each category differently. For studies in the empirical category, we read the methodology section of each paper and identified a) the type of habitat and taxonomic group(s) for which the debt was being evaluated, b) the source of data on those organisms, b) the method used to detect the extinction debt, d) whether the study estimated its duration (relaxation time) and magnitude (number of species yet to be extinct), and e) the spatial and temporal scales. We classified the methodology of each paper according to the summary presented in Kuussaari et al. (2009). Namely, these are i) regressive methods, ii) comparative methods, iii) estimations based on species-area relationships, iv) estimations from time series biodiversity data and v) (meta)population modeling (for a more thorough description of each method, please refer to Kuussaari et al. 2009). Methods that do not fall into those categories were specifically identified in Table A1 and classified as "Alternative methods" in Figs. 1, and Tables A1 and A2. Moreover, only estimations of the relaxation time made under a clearly stated assumption of new equilibrium of the system were considered estimations of relaxation time. We did not consider the time passed since the perturbation to be the relaxation time because it does not necessarily correspond to the time taken to pay the extinction debt. To identify whether any ecological mechanism was explicitly investigated in the study, we carefully read each paper, especially the section describing the methodology used, and searched for attempts to quantify factors related to the mechanism. For example, Guardiola et al. (2018) estimated associations between network metrics and current and past landscape metrics in a system paying an extinction debt. For that reason, we interpreted that the mechanism investigated was the loss of biological interactions during the relaxation time. Mechanistic explanations alluded to or presented in the discussion section were not considered as explicitly investigated and therefore are not listed.

Models in the theoretical category (listed in Table A2) were classified according to model (*e.g.*, mathematical, metapopulation, agent-based models) and theoretical background (*e.g.*, metapopulation, island biogeography, coexistence theories).

**Table A1**: List of reports of extinction debt published between 2009 and 2017. Papers are characterized according to (a) the ecological processes explicitly investigates, (b) the type of habitat where the debt was being evaluated, (c) the source of data on those organisms, (d) the causative perturbation of the extinction debt, (e) the taxonomic group(s) for which the debt was being evaluated, (f) the method used to detect the extinction debt, (g) whether the study estimated the magnitude of the extinction debt (i.e. number of species yet to be extinct), and (h) the spatial scale of the study. Studies published in 2009 where only included in this table if not present in Kuussaari et al. (2009).

| Reference | Processes investigated | Habitat | Data collection | Perturbation | Organisms | Method | Magnitude | Spatial Scale | Notes |
|---|---|---|---|---|---|---|---|---|---|
| Alignier and Aviron (2017) | no | Field margins | Field sampling | Cessation of management | Carabid beetles | Regression | no | Regional | - |
| Alofs et al. (2014) | no | Savanna | Field sampling | Cessation of management | Plants | Regression | no | Regional | - |
| Aynekulu et al. 2016) | no | Dry Afromontane forest | Field sampling | Direct exploitation | Woody Plants | Inferred from species absence in seed bank | 50% of current diversity | Local | - |
| Bagaria et al. (2015) | no | Mediterranean grasslands-forest interface | Field sampling | Forest encroachment | Plants | Regression | no | Regional | - |
| Bommarco et al. (2014) | no | Semi-natural grassland | Field sampling | Habitat destruction | Butterflies; Bees; Hoverflies; Vascular Plants | Regression | no | Regional | - |

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|---|---|---|---|---|---|---|---|---|---|
| Botzat et al. (2015) | Local population structure and metapopulation dynamics | Scarp forest | Field sampling | Habitat destruction | Tree; Seedling; Sapling | Inferred from reduced recruitment | no | Regional | - |
| Bunnell and Houde (2010) | no | Managed forest | Literature | Cessation of management | Vertebrates; Invertebrates | Inferred from review | no | Continental | - |
| Burst et al. (2017) | no | Forest-grasslands interface | Field sampling | Habitat destruction | Plants | Regression | no | Regional | - |
| Chen and Peng (2017) | no | Forest | Databases | Habitat destruction | Reptiles; Amphibians; Mammals | Neutral model | up to 100 species, depending on the group | Global | - |
| Cousins and Vanhoenacker (2011) | no | Semi-natural grasslands | Field sampling | Habitat destruction | Plants | Regression | no | Local; Regional | - |
| Cristofoli et al. (2010) | no | Wet heathlands | Field sampling | Habitat destruction | Vascular Plants | Regression | no | Regional | - |
| Cusser et al. (2015) | no | Agroecological system | Field sampling | Habitat destruction | Bees; Butterflies | Regression | no | Local; Regional | - |
| Ding et al. (2017) | no | Lakes | Field sampling | Species Introduction | Fish | Regression and Time-series data | no | Local; Regional | - |

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|---|---|---|---|---|---|---|---|---|---|
| | | | | | | for diversity | | | |
| Dullinger et al. (2012) | Local population and metapopulation dynamics | Alpine forest | Databases; Literature | Climate Change | Plants | Niche model | 44-50% range reduction | Regional | - |
| Dullinger et al. (2013) | no | NA | Databases | Habitat destruction | Vascular Plants; Bryophytes; Mammals; Reptiles; Dragonflies; Grasshoppers | Regression | no | Continental | - |
| Duplisea et al. (2016) | Local population dynamics | Sea bank | Databases | Direct exploitation | Fish; Invertebrates | Occupancy model | no | Regional | - |
| Ellis and Coppins (2009) | no | Juniper scrub | Field sampling | Climate Change; Fragmentation; Pollution | Lichen epyphites | Regression* | no | Regional | *Ordination analysis |
| Ernoult and Alard (2011) | no | Hedgerow networks | Field sampling | Habitat destruction | Vascular plants | Regression | no | Local; Regional | - |

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|---|---|---|---|---|---|---|---|---|---|
| Flensted et al. (2016) | no | Temperate forest | Databases; Literature | Climate change; Habitat destruction | Mammals; Saproxylic beetles; Butterflies; Vascular plants; Fungi | Regression | no | Regional | - |
| Fordham et al. (2016) | Metapopulation dynamics | Tropical forest | Literature | Climate change; Area loss | Frogs | Bioclimatic and nihe population models, compared to different species-area relationship estimates | 0-25 (scenario and model dependent) | Regional | - |
| Gibbs and Jiang (2017) | Interaction loss | Microcosm | Experiment | Environmental warming | Bactivore protists | Time-series data | yes | Microcosm | - |
| Gilbert and Levine (2013) | Metapopulation dynamics | Serpetine grasslands | Field sampling | Invasion | Grass | Metapopulation model | no* | Regional | Persistence estimation for a number of species |
| González-Varo et al. (2015) | no | Mediterranean woodland | Field sampling | Habitat destruction | *Myrtus Communis* | Regression* | no | Regional | * Quantified presence-absence, not richness |

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|---|---|---|---|---|---|---|---|---|---|
| Guardiola et al. (2013) | no | Mediterranean mountain grasslands | Field sampling | Cessation of management | Vascular plants | Regression; Comparison | 10 species | Regional; Local | - |
| Guardiola et al. (2018) | Interaction loss | Mediterranean mountain grasslands | Field sampling | Cessation of management | Vascular plants; Butterflies | Regression* | no | Regional; Local | *Regressions between network metrics and habitat conditions |
| Haddad et al. (2015) | no | Long Term Ecological Research Network (LTER) | Experiment | Habitat destruction | Plants; Arthropods; Birds; Butterflies | Lagged increase in extinctions | no | Regional; Global Comparison | - |
| Hahs and McDonnell (2014) | no | Urban area | Literature | Habitat destruction | Plants | Backward SAR | 55 % of current diversity | Local | - |
| Hahs et al. (2009) | no | Urban area | Literature | Habitat destruction | Plants | Backward SAR | up to 55%* | Local; Global Comparison | * Hahs and McDonnel (2009) is included in this global comparison |
| Highland and Jones (2014) | no | Meadow | Field sampling | Habitat destruction | Plants; Nocturnal moths | Regression | no | Regional | - |
| Huber et al. (2017) | no | Calcareous grasslands | Field sampling | Habitat destruction | Plants | Bayesian multiple regression | no debt | Regional | - |

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|---|---|---|---|---|---|---|---|---|---|
| Hylander and Nemomissa (2017) | no | Forest-agriculture mosaic | Field sampling | Habitat destruction | Epiphytes; Mosses; Liverworts | Regression* | no | Local | *Path model |
| Hylander and Weibull (2012) | no | Coniferous forest | Field sampling | Habitat destruction | Briophytes | Time-series data | no | Regional | - |
| Jimenez-Alfaro et al. (2016) | Genetic erosion | Mountain forests | Field sampling | Paleontological event | *Salix hastata*; *Juncus balticus* | Species distribution modeling; population genetics analysis | no | Regional | - |
| Jones et al. (2016) | no | Wet tropical, Subtropical, Mediterranean and Boreal forests; Tropical grassland | Literature | Habitat destruction | Mammals; Birds;Invertebrates; Herptiles; Plants; Fungi | Inferred from depaupered richness | no | Global | - |
| Klaus et al. (2012) | no | Coral reefs | Field sampling | Paleontological event | Coral | Inferred from extinction rates* | no | Regional | * Calculated from stratigraphic units |
| Kolk and Naaf (2015) | no | Temperate forest | Field sampling | Habitat destruction | Vascular herbs | Regression | no | Regional | |
| Koyanagi et al. (2017) | no | Semi-natural-grasslands | Observational | Habitat destruction | *Echinops setifer* | Regression | no | Local | - |

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|---|---|---|---|---|---|---|---|---|---|
| Krauss et al. (2010) | no | Calcareous grasslands; | Field sampling | Habitat destruction | Plants; Butterflies | Regression | no | Regional | - |
| Latta et al. (2017) | no | Premontaine forest | Field sampling | Habitat destruction | Birds | Population trends model | credit | Regional | - |
| Lehtilä et al. (2016) | Local population dynamics | Grasslands | Field sampling | Cessation of management | *Primula Veris* | Metapopulation model | no | Regional | - |
| Lira et al. (2012) | no | Atlantic forest | Field sampling | Habitat destruction | Birds; Mammals | Regression | no | Regional | - |
| May et al. (2013) | Metapopulation dynamics | Mediterranean schrub; grassland | Field sampling | Habitat destruction | Vascular Plants | Multi species incidence model | 33-60% | Regional | - |
| Neumann et al. (2017) | no | Woodland | Field sampling | Habitat destruction | Carabid beetles | Regression* | no | Regional | * Multivariate analysis, but still based on regressions |
| Niissalo et al. (2017) | no | Tropical forest | Observational | Habitat destruction | Zingiberales | Inferred from species distribution and extinction risk | no | Regional | - |

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|---|---|---|---|---|---|---|---|---|---|
| Ockinger and Nilsson (2010) | no | Hemi boreal forest | Field sampling | Habitat destruction | Epiphytic Lichens | Inferred from negative population growth | no | Local; Regional | - |
| Olivier et al. (2013) | no | Coastal forest | Field sampling | Habitat destruction | Birds | Backward SAR* | 14 spp. | Local; Regional | *Combined with species distribution model |
| Otsu et al. (2017) | no | Semi-natural grasslands | Field sampling | Habitat destruction | Plants | Hierarchical Bayesian regression model | no | Regional | |
| Otto et al. (2017) | no | Coastal vegetation; Euphorbia scrub; Thermophilous woodland; Laurel forest; Pine forest; Oceanic islands | Field sampling | Habitat destruction | Vascular Plants; Ground Beetles; Darkling Beetles; Flies; Land snails | Regression | no | Regional | - |
| Pandit et al. (2017) | no | Freshwater system | Literature data; Secondary sources | Climate Change | Fish | Species distribution model | no* | Regional | *Estimation of range shift,extinctoin debt being inferred for potentially isolated populations |

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|---|---|---|---|---|---|---|---|---|---|
| Piqueray et al. (2011a) | no | Calcareous grasslands | Field sampling | Habitat destruction | Plants | Regression and Comparison | 28.00% | Regional | - |
| Piqueray et al. (2011b) | no | Calcareous grasslands | Field sampling | Habitat destruction | Plants | Comparison | 20.3 – 34.1 % | Regional | - |
| Plue et al. (2017) | Genetic erosion and Local population structure | Semi-natural grasslands | Field sampling | Habitat destruction | *Campanula rotundifolia* | Regression* | no | Regional | * Genetic extinction debt inferred from Regression |
| Rédei et al. (2014) | | Sand grassland | Field sampling | Habitat destruction | Plants | Regression and Comparison | no | Regional | - |
| Rogers et al. (2009) | no | Forest understory | Field sampling | Habitat destruction | Plants | Regression | no | Regional | - |
| Saito et al. (2016) | no | Urban-rural gradient | Field sampling | Habitat destruction | Hare | Inferred from presen in regressive site | no | Local | - |
| Sang et al. (2010) | no | Calcareous grasslands | Field sampling | Habitat destruction | Butterflies | Regression | no | Regional | - |
| Soga and Koike (2012) | no | Decidous forest | Field sampling | Habitat destruction | Butterflies | Regression; Comparison | 0.3-3.8 spp. | Regional | - |
| Szabo et al. (2011) | no | Woodlands | Field sampling | Habitat destruction | Birds | List length | no | Regional | - |

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|---|---|---|---|---|---|---|---|---|---|
| Takkis et al. (2013) | Genetic erosion and Local population dynamics | Calcareous grasslands | Field sampling | Habitat destruction | *Briza Media* | Regression | no | Regional | - |
| Talluto et al. (2017) | Metapopulation dynamics | Temperate-boreal forest | Databases | Climate Change | Trees | Metapopulation model* | yes (mapped) | Regional | *Combined with distribution modelling |
| Thijs et al. (2014) | Metapopulation dynamics | Afromontane forest | Field sampling | Habitat destruction | Trees | Species equation | 9.00% | Regional | - |
| Triantis et al. (2010) | no | Laurisilva forest | Literature | Habitat destruction | Coleoptera; Hemiptera; Araneae | Backward SAR* | 67-91%** | Regional | *Species-area-age relationship; ** Varying for taxonomical group and at the local scale |
| Uezu and Metzger (2016) | no | Atlantic forest | Field sampling | Habitat destruction | Birds | Regression | no | Regional | - |
| Wearn et al. (2012) | no | Amazonian forest | Databases | Habitat destruction | Vertebrates | Dynamic SAR | 16 spp. | Regional | - |
| Yamanaka et al. (2015) | Individual survival | Oak forests | Field sampling | Habitat destruction | Carabid beetles; Bats | Regression | no | Regional | - |

**Table A2:** List of studies considered to be 'theoretical work. These studies are modelling explorations of different aspects of extinction debt (specified in the *Motivation* column).

| Reference | Modelling strategy | Theoretical framework(s) | Explicitly simulated processes | Simulated impact | Motivation | Empirical verification | Mechanistic findings | Considerations on spatio-temporal |
|---|---|---|---|---|---|---|---|---|
| Chen et al. (2009). | Multi-species hierarchical competition model | Metapopulation theory | Mortality, colonization, competition | Habitat loss | To verify the importance of Allee-like effect on extinction debt size and order. | no | Allee efect affects the extincitons order and the extinction debt; the stronger the Allee effects, the more sensitive species are to habitat destruction. | Strong Allee effect decreases time lag of extinction but also depends on the initial abundance of the best competitor. |
| Orrock and Watling (2010) | Hierarchical competition model | Metapopulation, Neutral and Niche theories | Mortality, colonization, competition | Habitat (patch) loss and degradation (reduction in community size) | To verify relative roles of niche and neutral dynamics in metacommunities. | no | In small comminuties, demographic stochasticity has stronger effect on species survival than competitive ability. | - |

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|---|---|---|---|---|---|---|---|---|
| Halley and Iwasa (2011) | Hyperbolic model of relaxation time | Neutral theory | Phenomenological model: Relaxation curve derived from species abundance distribution | Habitat loss | To predict extinction rates. | yes | - | Estimations from the neutral model agree well with data for large areas (1-$10^3$ $km^2$) ; immigration, isolation, behavioural shifts and environmental stochasticity are likely more relevant in small fragments, where the neutral model underestimated relaxation times; in very large fragments, speciation, immigration and endemicity might explain overestimations yielded by the neutral model; estimation of extintion times based on the broken-stick produce better fit than the ones based on the log-series model. |
| Mouquet et al. (2011) | Source-sink metacommunity models | Niche and Metapopulation theory | Competition, reproduction, mortality, dispersal | Habitat destruction (via removal of local communities) | To verify effects of landscape perturbation on species coexistence (under competition-colonization trade-off) under source-sink dynamics. | no | Dispersal and relative competitive abilities generate different patterns of extinction, depending on the importance of source-sink dynamics. | Extinctions resulting “directly” from habitat loss (*i.e.* loss of source populations) happen faster than “indirect” extinctions, resulting from decreased regional similarity between species competitive abilities; the relaxation time for direct extinctions increases with dispersal but not for very low regional similarity, where source-sink dynamics are less relevant. |

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|---|---|---|---|---|---|---|---|---|
| Claudino et al. (2015) | Individual-based model | Neutral theory | Mortality, speciation, dispersal | Habitat fragmentation | To verify the impact of dynamic fragmentation on extinction debts. | no | Dispersal leads to lower biodiversity than SAR estimations in a scenario of dynamical disturbance. | The time between disturbance events affects the extinction debt but not their magnitude. Destruction of contigous fractions of habitat lead to smaller extinctoin debts. |
| Huth et al. (2015) | Metapopulation model | Metapopulation theory | Colonization, extinction | Habitat fragmentation | To differentiate the role of short and long-distance dispersal in the maintenance of regional persistence in fragments | no | - | Large islands dominate the slow dynamics of extinction away from the critical threshold; slow extinction dynamics due to heterogenous island size distribution is different from extinction debt. |
| Kitzes and Harte (2015) | Mathematical model | Neutral theory | Phenomenological model | Habitat loss (including climete-driven range contraction) | To verify how abundance distribution and spatial aggregation affect the magnitude of extinciton debt. | yes | - | Communities following lognormal and broken-stick abundance distributions will present extinction debt under low spatial aggregation, or immgiration credit under high aggregation; increasing species spatial aggregation decreases the extinction debt. |

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|---|---|---|---|---|---|---|---|---|
| Halley et al. (2016) | Population-based model | Neutral and island biogeography theories | Extinction | Habitat loss | To describe dynamics of extinction debts. | yes | - | Half-life of extinction and time to first extinction increase with remnant area; biodiversity loss might not be detected if surveys are conducted too early (before first extinction) or too late (after the debt has been paid). |
| Chen and Shen (2017) | Expansion of the model by Kitzes and Harte (2015) | Neutral theory | Phenomenological model | Habitat loss | To include time delayed responses in the model of Kitzes and Harte (2005). | no | - | Depending on the species distributions and the pattern of habitat destruction, species contribute to either extinction debt or immigration credit. |
| Hugueny (2017) | Species loss equation | Neutral and island biogeography theories | Phenomenological model wih diversity dependent extinction rate | Habitat fragmentation (increased isolation) | To account for area and age of fragments/islands and diversity-dependence when estimating extinction rates over large time intervals. | yes | Isolate age, rather than diverisity-dependence, has a stronger impact on species loss rates | - |
| Sgardeli et al. (2017) | Neutral model community model | Neutral theory | Extinction, speciation | Any disturbance | To derive the relaxation curve for neutral communities where speciation introduces new species | no | - | Relaxation time is quicker for higher speciation rates, which depends on community size. |

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|---|---|---|---|---|---|---|---|---|
| Zarada and Drake (2017) | Population logistic model | Population theory | Birth, Death | Any disturbance (via effects on birth and death rates) | To verify extinciton times in continuously deteorating environments | no | Population dynamics alone (ignoring metapopulation dynamics) can have important effects on extinction delays. | When birth rates are affected by declining carrying capacity, extinction delay is the largest, but extinction debt is the smallest. The contrary is true when mortality rates are affected. |

**Table A3**: List of studies addressing issues arising from estimations of extinction debts using species-area relationships (SARs) or endemics-area relationships (EARs) using an alternative modelling strategy (other studies addressing the same issue are listed in the main text).

| Reference | Modelling strategy | Theoretical framework(s) | Explicitly simulated processes | Empirical verification | Motivation | Mechanistic findings | Considerations on area-based estimations (SARs or EARs) |
|---|---|---|---|---|---|---|---|
| Halley et al. (2014) | Neutral model of relaxation time | Neutral and Metapopulation theories | Reproduction, mortality, dispersal (immigration) | yes | To understand SAR estimations in the context of extinction debt. | Inclusion of immigration helps differentiate between imminent and delayed extinctions. | Two SAR curves emerge, one predicting immediate extinctions, and one predicting the total number of extinctions. The difference between the two is the number of delayed extinctions (*i.e.* the total extinction debt). |
| Matias et al. (2014) | Individual-based spatially-explicit model | Niche, Neutral and Community assembly theories | Mortality, reproduction, dispersal, competition, coexistence mechanisms | no | To verify SAR estimations of extinctions | Coexistence mechanisms and environmental heterogeneity affect species abundance distributions, which affect how species respond to different patterns of habitat loss. | SARs and EARs underestimate extinctions; SAR estimations are higher than EARs and closer to equilibrium values, indicating that EARs are better suited for estimations of immediate loss; both effects were higher with higher habitat-loss. |

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|---|---|---|---|---|---|---|---|
| Rybicki and Hanski (2013) | Spatially explicit stochastic patch occupancy model | Metapopulation and Niche theories | Colonization, extinction, dispersal | no | To compare SAR and EAR estimations of extinctions in a dynamic context of habitat fragmentation. | SAR are unlikely to have the same slopes in areas where species distribution is more affected by spatial dynamics (low dispersal between isolated fragments). | Remaining species-area relationship underestimates future extinctions; SARs produce large underestimations in highly fragmented landscapes with small areas of remnant habitat. |
| Tanentzap et al. (2012) | Probabilistic endemic species-area relationship | Island biogeography and Metapopulation theories | Phenomenological model | yes | To adapt EAR to account for future extinctions. | Population size and remnant habitat area influence delayed extinctions. | EARs underestimate future extinctions. However, it is possible to adapt EARs to include the effects of population size and remnant habitat area that generate delayed extinctions. |

**Table A4**: List of studies reporting extinction debts for which information regarding the spatial and/or temporal scales was retrieved. Details on how the scales were identified – or not – are specified in the *Observation* column. Studies from Table A1 which reported that the debt had already been paid where not plotted. Notation used to describe the frequency of data compilation: ";" indicates repeated measures, and "-" indicates a range of dates where measures were taken (regularly or not). Values marked with * entail further details in the *Observation* column.

| Reference | Biodiversity sampling | Begin of disturbance | Habitat condition data/ Simulation duration | Age/ Duration of debt (years) | Focal habitat area (km²) | Observation |
|---|---|---|---|---|---|---|
| Alignier and Aviron 2017 | 2001/2002 | NA | 1995-2002* | 5 | NA | * Annually measured |
| Alofs et al. 2014 | 2007 | NA | 1951; 1980; 1995; 2004; 2008 | 56 | 33.43* | * Sum of 3 study sites |
| Aynekulu et al. 2016 | NA | NA | NA | NA | 16.87 | - |
| Bagaria et al. 2015 | 2011 | 1940 | 1956; 2009 | 55 | 320* | * Total study area |
| Bommarco et al. 2014 | 2007 | NA | 1952-2005* | 12 | 2.0205* | * Measures taken at variable intervals<br>** Approximated from mean patch area (45 patches) |
| Botzat et al. 2015 | 2010 | 1860* | NA | ~150* | NA** | * Approximated from range informed in the text<br>** Unable to approximate total area from map |
| Bunnell and Houde 2010 | NA | NA | NA | NA | NA* | * Unable to approximate total area from compiled literature |
| Burst et al. 2017 | 2014 | 1826 | 1931-2014* | 21 | 2000* | *Measures taken approximately every decade.<br>** Total study area |
| Chen and Peng 2017 | NA | NA | 1500; 2000; 2005 | Not applicable | Not applicable | * Global study |

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|---|---|---|---|---|---|---|
| Cousins and Vanhoen 2011 | 2005 | NA | 1901 | 14 | 2250 | * Total study area |
| Cristofoli et al. 2010 | 2006 | NA | 1770; 1880; 1950; 1970; 2006 | 236 | 17.65* | * Current total area of focal habitat in the study area |
| Cusser et al. 2015 | 2013 | NA | 1992; 2006 | 21 | 6 | * Current total area of focal habitat in the study area |
| Ding et al. 2017 | 1940-2015 (literature data) | 1958-1965; 1970-1980 | same as biodiversity | 50 | 1102.5* | *Sum of lakes areas |
| Dullinger et al. 2012 | Not applicable * | NA | 2010-2100 (simulation) | > 100* | Not applicable * | * Predictions of range decline |
| Dullinger et al. 2013 | 1995-2010 (national redlist data) | NA | 1900; 1950; 2000 | 110 (plants, insects, mammals); 10 (fishes, reptiles) | NA* | * Unable to determine total area, because focus is on organisms |
| Duplisea et al. 2016 | 1963-2008 (annual) | 1800* | Not applicable | 45 | ~28800** | * Approximated value<br>** Approximated from map<br>https://soundwaves.usgs.gov/2005/01/fieldwork4.html |
| Ellis & Coppins 2009 | 2005/2006 | NA | 1961-2000 (climate); 1869 – 2004 (fragmentation); | 44 (climate); 136 (fragmentati on) | NA* | * Unable to approximate total area from map |
| Ernoult & Alard 2011 | 2001 | 1950 | 1963; 1985; 2000 | 38 | NA* | * Unable to approximate total area from map |
| Flensted et al. 2016 | 1994-2013* | NA | 1760-1850; 2013 | 200 | 6081** | * Database collection<br>** Current total area of focal habitat in the study area |

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|---|---|---|---|---|---|---|
| Fordham et al. 2014 | Williams SE et al. 2010 | NA | 2080; 2150; 2200 (predictive) | 100* | NA | * Predictive model |
| Gibbs & Jiang 2017 | | Microcosm experiments | | | Not applicable | - |
| Gonzales-Varo et al. 2015 | 1999;2001 | 1500 | 1956; 2002 | 45 | 21 000** | * Approximated value<br>** Total study area |
| Guardiola et al. 2017 | 2007 | NA | 1956; 2003 | 47 | NA | - |
| Haddad et al. 2015 | | | Mesocosm experiments | | | - |
| Hahs et al. 2009 | 1800-1900;1980-2000(literature and unpublished datasets) | 1600-1800 | Not applicable | 250 | NA | * Approximated value |
| Highland & Jones 2014 | 2008-2010 (annual) | NA | 1949;2005 | 61 | NA | - |
| Huber et al. 2017 | 2013* | NA | 1830;2013 | no debt | no debt | * Assumed to be present date |
| Hylander & Nemomissa 2017 | 2008-2009 | NA | 1967-2008 | 7 | 900 | * Total study area |
| Hylander & Weibull 2012 | 1998; 2001, 2009 | 1998 | NA | 10 | 0.013 * | * Sum of area of compared plots |
| Jimenez- Alfaro et al. 2016 | NA(present) | NA | LGM (niche models) | 21000; 1000* | NA | * Exact values depends on location |

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|---|---|---|---|---|---|---|
| Jones et al. 2016 | 1982-2015 (1-92 years since disturbance) | 1916-2000 | Not applicable | NA | NA* | * Literature data |
| Klaus et al. 2012 | 1993-2009* | NA | ~ 3.5 Ma | ~1500000** | NA | * Collection of stratigraphic units<br>** Time between Oceanic closure of the Central American Seaway and the peak in extinctions |
| Kolk and Naaf 2015 | 2013 | NA | 1780; 2008 | 160* | 4217 ** | * Duration of payment<br>** Total study area |
| Koyanagi & Akasaka 2017 | 2008/2009 | 1930 | 1930; 1970; 2000 | 78 | NA | - |
| Krauss et al. 2010 | 2001(plants); 2007 (butterflies) | Estonia: 1930* | Estonia: 1968;2005 | no debt at local scale | 10.117 ** | * Approximated value<br>** Estimated from current mean patch area (sampled patches) |
| Krauss et al. 2010 | 2000 | Finland: 1880* | Finland: 1963/65;1999-2005 | no debt at local scale | 0.468** | * Approximated value<br>** Estimated from current mean patch area (sampled patches) |
| Krauss et al. 2010 | 2000 | Germany: 1900* | Germany: 1962*; 2004-2005 | 38 | 0.5177 ** | * Approximated value<br>** Estimated from current mean patch area (sampled patches) |
| Krauss et al. 2010 | 2007 | Spain: 1940* | 1956, 2004 | no debt at local scale | 1.515** | * Approximated value<br>** Estimated from current mean patch area (sampled patches) |
| Krauss et al. 2010 | 2007 | Sweden: 1900* | 1956-59*; 2003 | no debt at local scale | 1.38** | * Approximated value<br>** Estimated from current mean patch area (sampled patches) |
| Lehtila et al. 2016 | 1995-1998,2006 | NA | NA | 40-250 | NA | - |

| | | | | | | |
|---|---|---|---|---|---|---|
| Lira et al. 2012 | 2001-2002/2004-2005/2005-2007 | 1500* | 1962; 1979-1981;2000-2005 | 40, 20 | 100** | * Approximated value<br>** Total study area |
| May et al. 2013 | 2009; 2010/2011 | NA | 1000 years | <1000* | NA | * Simulation duration |
| Neumann et al. 2017 | 2011 | 1940* | 1930; 2011 | 81 | 1.178** | * Approximated value<br>** Estimated from current mean woodland patch area (sampled patches) |
| Niisalo et al. 2017 | 1989-2005* | 1819 | NA | 200 | 20 | * Varying intervals for each population |
| Öckinger & Nilsson 2010 | 1989-1998;2001-2005 | Not applicable | Not applicable | 16 | 6720* | * 70% of study region (total = 9600 $km^2$) is covered in forest |
| Olivier et al. 2013 | 2011/2012 | <1800 | Backward SAR | NA | 663* | * Total coastal forest area |
| Otsu et al. 2017 | 1984; 1985, 1986; 2008-2010 | 1800* | 1910; 1980/2000 | 100 | 25200 ** | * Approximated value<br>** Total study area |
| Otto et al. 2017 | literature data | 1400* | NA (approximated conditions) | 600 | 7447** | * Approximated value<br>** Total study area |
| Pandit et al. 2017 | literature/data bases | NA | 70 years* | 70* | NA | * Simulated (1908-2050) |
| Piqueray et al. 2011 | 2002; 2003 | 1920* | 1920; 1965; 2002 | 82, 37 (model-dependent) | 0.59 ** | * Approximated value<br>** Current total area of focal habitat in the study area |
| Plue et al. 2017 | 2011 | 1854 | 1954; 2011 | 57 | 25* | * Total study area |

| | | | | | | |
|---|---|---|---|---|---|---|
| Redei et al. 2014 | 2007 | 1800* | 1783;1860;1950; 1987/1989; 2005 | 147 | NA | * Approximated value |
| Rogers et al. 2009 | 1950;2005 | NA (European settlement) | 1950 (approximated); 2005 | no debt | 39215* | * Approximation of total study area occupied by sampled sites from map provided in paper |
| Saito et al. 2016 | 2006-2007 | 1940 | 1950;1974;1984; 1994 | 30 | NA | - |
| Sang et al. 2010 | 2007-2008 | 1930* | 1930; 2004 | 77 | 78** | * Approximated value<br>** Current total area of focal habitat in the study area |
| Soga & Koike | 2011 | 1970* | 1971;2011 | 40 | NA | * Approximated value |
| Szabo et al. 2017 | 1997-2007 (annual) | 1800* | Not applicable | 60 | 0.02** | * Approximated value<br>** Total study area |
| Takkis et al. 2013 | 2008;2011 | 1930 | 1930;2000 | 78 | 8.95* | * Sum of current areas of sampled patches |
| Talluto et al. 2017 | NA | NA | 1945-2010 | 65 | NA | - |
| Thijs et al. 2013 | NA | *1800 | Not applicable | 200 | 4.13** | * Approximated value<br>** Total area of flores relicts |
| Triantis et al. 2010 | 1859-2010 | 1400* | 1440;1700;1850; 200 | ~570 ** | 58 km² *** | * Approximated value<br>** SAR from 1700 also used for estimate the extinction debt,<br>*** Remaining native forest area |
| Uezu & Metger 2016 | 2003; 2004; 2005 | 1950 | 1956; 1965; 1978; 1993; 2003 | 26 | 380* | * Current forest cover corresponds to 19% of original 200000 ha |

| | | | | | | |
|---|---|---|---|---|---|---|
| Wearn et al. 2012 | NA (IUCN) | 1970 | 1978; 1988; 1992; 1998; 2000-2008 (annual); 2050 (simulation) | 80* | 5500000** | * Simulation duration;<br>** Total area of Amazonian region covered in the simulations (Fig. 1 of Wearn et al. 2012). |
| Yamanaka et al. 2015 | 2011 | 1896 | 1920, 1957, 2000 | 50 | 4500 $km^2$ * | * Total study area estimated from Fig. 1 |

**List A1:** List of papers arising from the literature search and which discuss relevant points related to extinction debts. These papers, however, do not fit the ‘empirical’, ‘theoretical’ nor ‘methodological work’ categories. These papers are cited throughout the text when relevant.


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Osmond, M. M. and Klausmeier, C. A. 2017. An evolutionary tipping point in a changing environment. - Evolution 71: 2930–2941.

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Saar, L. et al. 2012. Which plant traits predict species loss in calcareous grasslands with extinction debt? - Diversity and Distributions 18: 808–817.
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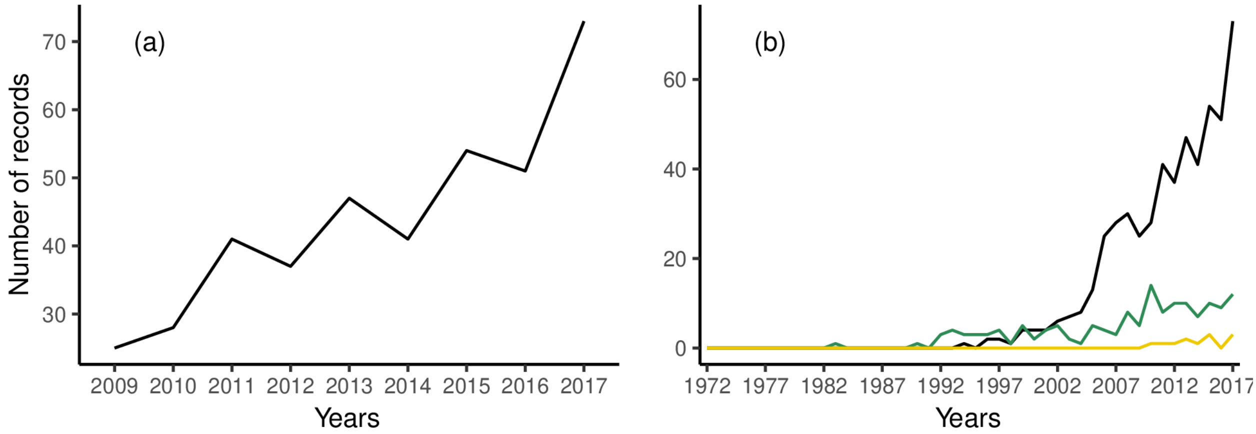


**Figure A1**: Number of records returned by different searches in the Web of Science collection. (a) Number of hits of "extinction debt", between 2009 and 2017 (total = 397). (b) Number of manuscripts returned for the strings "extinction debt" (black), "relaxation time" (restricted to the Environmental Sciences & Ecology research area – green, *n* = 147) and “relaxation time AND extinction debt” (yellow, *n* = 12 - first one published in 2010), between 1972 and 2017.

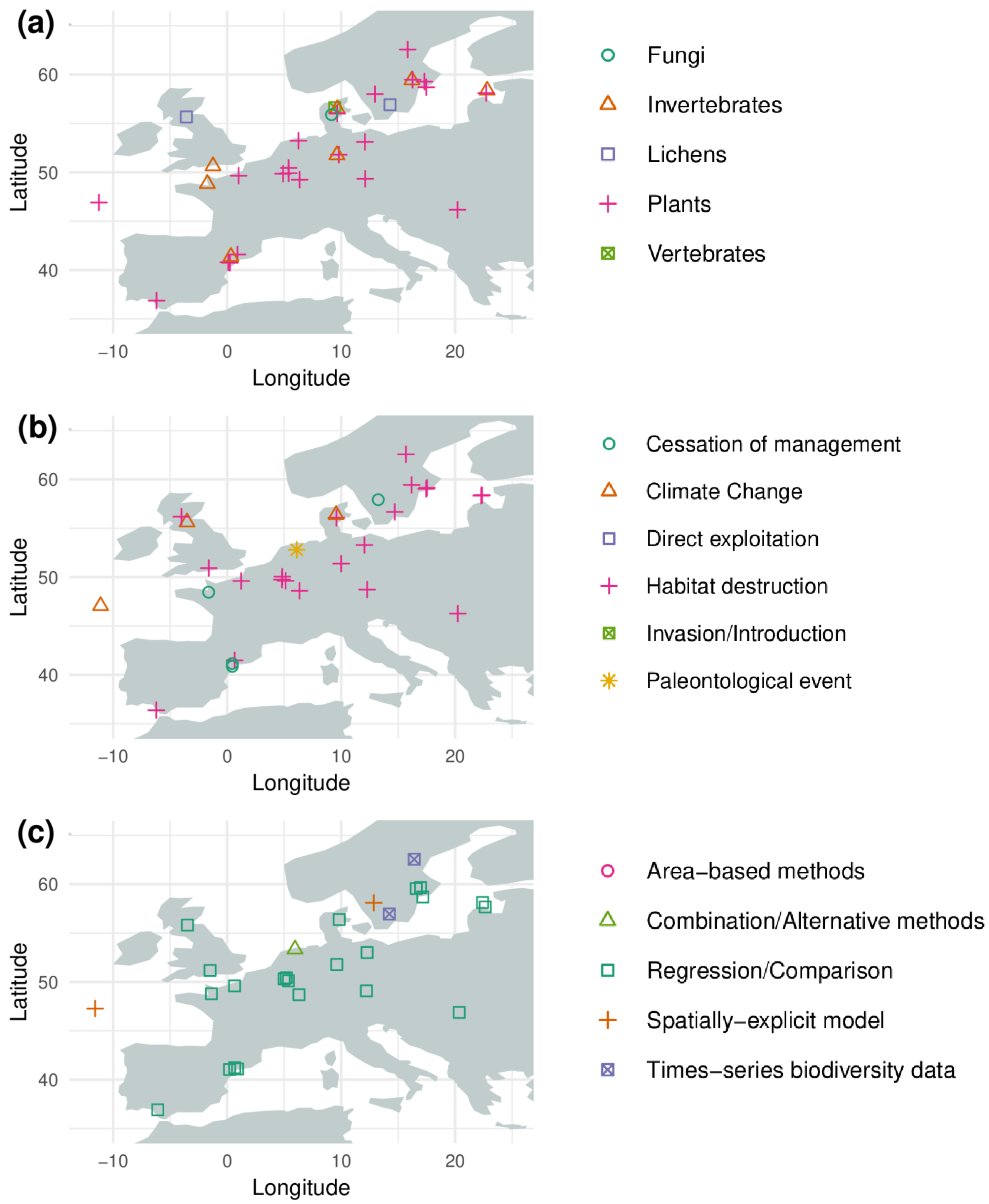


**Figure A2:** Distribution of (a) taxonomic groups for which extinction debt was investigated, of (b) the causative perturbations behind the possible extinction debts, and of (c) the methods applied in the studies. All panels include empirical studies investigating extinction debts in European real-world systems, published between 2009 and 2017. All studies are listed in Table A1 (studies at the continental ($n$ = 2), global ($n$ = 4) or microcosmic ($n$ = 1) scales were not included).

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