The broad footprint of climate change from genes to biomes to people

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BACKGROUND: Climate-change impacts have now been documented across every ecosystem on the Earth, despite an average warming of only ~1°C so far. Here, we describe the full range and scale of climate-change effects on global biodiversity that have been observed in natural systems. To do this, we identify a set of core ecological processes (32 in terrestrial and 31 in each of marine and freshwater ecosystems) that underpin ecosystem functioning and support services to people. Of the 94 processes considered, 82% show evidence of impact from climate change in the peer-reviewed literature. Examples of observed impacts from meta-analyses and case studies go beyond well-established shifts in species ranges, and changes to phenology and population dynamics to include disruptions that scale from the gene to the ecosystem scale.

ADVANCES: Species are undergoing evolutionary adaptation to temperature extremes, and climate change has significant impacts on species physiology that include changes in tolerances to high temperatures, shifts in sex ratios in species with temperature-dependent sex determination, and increased metabolic costs of living in a warmer world. These physiological adjustments have observable impacts on morphology, with many species in both aquatic and terrestrial systems shrinking in body size because large surface-to-volume ratios are generally favoured under warmer conditions. Other morphological changes include reductions in melanism to improve thermoregulation, and altered wing and bill length in birds.

Broader scale responses to climate change include changes in the phenology, abundance and distribution of species. Temperate plants are budding and flowering earlier in spring and later in autumn. Comparable adjustments have been observed in marine and freshwater fish spawning events and in the timing of seasonal migrations of animals worldwide. Changes in the abundance and age-structure of populations have also been observed with widespread evidence of range expansion in warm-adapted species and range contraction in cold-adapted species. As a by-product of species redistributions, novel community interactions have emerged. Tropical and boreal species are increasingly incorporated into temperate and polar communities, respectively and when possible, lowland species are increasingly assimilating into mountain communities. Multiplicative impacts from gene to community levels scale up to produce ecological regime shifts — where one ecosystem state shifts to an alternative state.

OUTLOOK: The many observed impacts of climate change at different levels of biological organization points towards an increasingly unpredictable future for humans. Reduced genetic diversity in crops, inconsistent crop yields, decreased productivity in fisheries from reduced body size, and decreased fruit yields from fewer winter chill events threaten food security. Changes in the distribution of disease vectors alongside the emergence of novel pathogens and pests are a direct threat to human health as well as to crops, timber, and livestock resources. Humanity depends on intact, functioning ecosystems for a range of goods and services. Enhanced understanding of the observed impacts of climate change on core ecological processes is an essential first step to adapting to them and mitigating their influence on biodiversity and ecosystem service provision.

Abstract: Most ecological processes now show responses to anthropogenic climate change. In terrestrial, freshwater and marine ecosystems, species are changing genetically, physiologically, morphologically and phenologically, and are shifting their distributions, which impact food webs and result in new interactions. Disruptions scale from the gene to the ecosystem and have documented consequences for people, including unpredictable fisheries and crop yields, loss of genetic diversity in wild crop varieties, and increasing impacts of pests and diseases. In addition to the more easily observed changes such as shifts in flowering phenology, we argue that many "hidden" dynamics, such as genetic changes, are also taking place. Importantly, understanding shifts in ecological processes can guide human adaptation strategies. In addition to reducing greenhouse gases, climate action and policy must therefore focus equally on strategies that safeguard biodiversity and ecosystems.

Introduction

Atmospheric concentrations of greenhouse gases from burning fossil fuels and deforestation are approaching levels not detected for 20 million years (*1*). This has altered the chemical composition of the Earth's atmosphere, oceans and fresh waters (*2*). As a result, temperatures in the upper ocean and on land are now ~ 1^{o}C higher than in pre-industrial times, and temperature, wind and precipitation regimes have become more variable and extreme (*3*, *4*). These changes are having clear impacts on planetary biophysical processes, including desalinization and acidification of the world's oceans (*5*) and melting of permafrost, ice sheets, and glaciers (*6*, *7*). Lakes and rivers have increased in temperature, altering seasonal patterns of mixing and flows (*8*).

Changing climate regimes have been an important driver of natural selection in the past (*9*) and, as in the past, species are responding to the current human-induced climate event in various ways. Previous reviews have covered many of the more obvious changes in species ranges, phenology and population dynamics (*10–15*), but have usually focused on one ecological system at a time. Here, we discuss the full range and scale of climate change effects on biota, including some of the less obvious disruptions observed in natural systems. We present examples of case studies of observed impacts across terrestrial and aquatic biomes and find evidence that climate change is now affecting most biological and ecological processes on Earth–spanning genetics, organismal physiology and life-history, population distributions and dynamics, community structure and ecosystem functioning (Fig. 1 and Table S1). People depend on intact, functioning ecosystems for a range of goods and services, including those associated with climate adaptation (*16*). Understanding the observed impacts of current climate change on core ecological processes is therefore an essential first step in humans planning and adapting to changing ecosystem conditions.

Although inherently different, marine, terrestrial and freshwater realms share a common hierarchy of levels of biological organization, ranging from genes to organisms, populations, species, communities, and ecosystems. Broadly adapting from Bellard *et al.* (*17*), we screened the literature (see Supplemental Material for further details) to evaluate evidence that climate change is impacting ecological components across different levels of biological organization, each of which comprises a core set of ecological processes (Fig. 1 & S1 and Table S1). We identify a set of core ecological processes on Earth (32 in terrestrial and 31 in each of marine and freshwater), which together facilitate ecosystem functioning that support services to people (*17*). These processes include changes in genetic diversity (genetics), metabolic rates (physiology), body size (morphology), migration (phenology), recruitment (population dynamics), range size (distribution), loss of synchronization (interspecific relationships) and biomass (productivity) (*17*). As our main goal is to assess what processes are affected by climate change, we define 'impact' upon each process as an observed change in that process linked to climate change. We do not differentiate between "positive" (adaptive, buffering, mitigating) and "negative" (stress, damage) responses because responses may be "positive" at one level of biological organization (e.g., genetic adaptation to climate change) but "negative" at another (e.g., reduced genetic variation and capacity to deal with other stressors). We then consider the relevance of the impacted ecological processes in human systems and illustrate observed impacts to ecosystem services such as food and resource security (fisheries, agriculture, forestry and livestock production), human health and hazard reduction.

Ecological impacts of climate change

Organisms

Genetics

There is now growing evidence that species are undergoing evolutionary adaptation to human-induced climate change. For example, between the 1960s and 2000s, the water flea (*Daphnia magna*) evolved to cope with higher thermal extremes in the United Kingdom (*18*), and cornflower (*Centaurea cyanus*) life history traits have recently evolved in response to warmer springs across northern France (*19*). Other examples include the evolution of earlier migration timing in anadromous pink salmon (*Oncorhynchus gorbuscha*), with decreased frequency of incidence of a genetic marker that encodes for late-migration (*20*). Time-series data that control for physiological acclimatization also show strong evidence for genetic responses to climate change. For example, Bradshaw and Holzapfel (*21*) showed that genotypic values for the critical day length that induces diapause in the pitcher plant mosquito (*Wyeomyia smithii*) change with latitude, and that the latitudinal relationship has changed over the period 1972-1996. Onset of diapause now occurs later, consistent with a longer growing season under warmer conditions. Oceanic phytoplankton have adapted to a temperature change of +0.73 °C associated with 15 years of climate warming in the Gulf of Cariaco, Venezuela by adjusting their thermal niche by +0.45 °C (*22*). While such evidence from small organisms with short generation times is accumulating, we found little documented evidence of evolutionary change from species with longer generation times such as birds, mammals, and trees (*14*, *23*), although adaptation appears to be possible in some long-lived reef corals (*24*).

Changes in species ranges have altered or created new 'hybridization zones' across the planet. For example, in North America, hybrid zones between black-capped (*Poecile atricapillus*) and Carolina chickadees (*P. carolinensis*) are shifting in response to warmer winter temperatures (*25*), and as the southern flying squirrel (*Glaucomys volans*) expands its range northward in eastern North America it is now hybridizing with the northern flying squirrel (*G. sabrinus*) (*26*). In North American rivers and streams, hybridization between invasive rainbow (*Oncorhynchus mykiss*) and native cutthroat (*O. clarkia*) trout has increased in frequency as rainbow trout expand into warming waters (*27*). Such hybridization events have also been observed in some marine fishes such as the coastal fish *Argyrosumus coronus* and are expected to increase as species shift their ranges poleward in response to rapidly warming ocean conditions (*28*).

Physiology

Many species display temperature-driven trait plasticity in physiological processes such as thermal optima (*29*). While some responses, such as acclimation to high temperatures, maximize fitness, others can reflect failure to cope with temperature stress and other climate-mediated changes. These responses can occur within a generation or between generations through maternal or epigenetic effects (*30*).

There is some observational evidence that warming has impacted temperature-dependent sex determination (TSD) of species in marine and terrestrial systems. Snake pipefish (*Entelurus aequoreus*) in the northeastern Atlantic have altered their operational sex ratios and reproductive rates as a consequence of warmer sea surface temperatures (*31*). Most evidence for impacts on TSD in marine systems, however is derived from experimental studies, which provide strong support for TSD changes in sea turtles and fish (*32*, *33*). In terrestrial and freshwater systems, TSD has been implicated in masculinization and feminization, respectively, of lizard and turtle populations (*34*, *35*).

In marine systems, physiological responses to both climate warming and changing ocean conditions are widespread (*36*, *37*). Matching field and laboratory data for the eelpout (*Zoarces viviparus*) show increased metabolic costs associated with warming in the North and Baltic Seas (*38*). In aquatic systems, warming increases oxygen demand but decreases oxygen content of the water, resulting in substantial metabolic costs (*39*). Although climate change *per se* does not cause acidification of the oceans, both arise directly from higher atmospheric carbon dioxide, and experimental evidence has raised concerns regarding negative effects of ocean acidification on calcification, growth, development and survival of calcifying organisms (*12*). For example, acidification has led to extensive shell dissolution in populations of the pteropod, *Limacina helicina*, in northwest North America and in the Southern Ocean off Antarctica (*40*, *41*).

Morphology

Individuals in some species are becoming smaller with increasing warming because large surface-to-volume ratios are generally favoured under warmer conditions (*42*)—a phenomenon that is linked to standard metabolic principles (*43*). In the Appalachian Mountains, six species of *Plethodon* woodland salamander have undergone, on average, an 8% reduction in body size over the past 50 years (*44*). Similarly, three species of passerine birds from the northeast United States show an average 4% decrease in wing length correlated with recent warming (*45*) and the long-distance migrant bird red knot (*Calidris canutus*) is now producing smaller offspring with smaller bills, which reduced survival in juveniles due to altered foraging success on underground bivalves (*46*). In general, decreasing body size with warming is expected but evidence from cold, high altitude habitats suggests that increased primary productivity, and longer-growing seasons from warming has led to increased body size in some mammal species such as American marten (*Martes americana*) and yellow-bellied marmot (*Marmota flavientris*) (*47*, *48*). In South Australia, leaf width in soapberry (*Dodonaea viscosa)* has decreased compared to the ancestral condition documented under cooler temperatures 127 years ago (*49*). Other climate change impacts on morphology include colour changes in butterflies, dragonflies and birds (*50–53*) and pronounced changes in skull shape in alpine chipmunk (*Tamias alpinus*) (*54*).

Population

Phenology

For most species, migrations and life-history processes (such as budding and flowering in plants, hatching and fledging in birds, and hibernation in mammals) are closely tied to seasonal and interannual variation in climate, and there is now overwhelming evidence that both have been impacted by climate change (*10*, *37*, *55*, *56*). Across marine, freshwater and terrestrial ecosystems, spring phenologies have advanced by -2.3 to -5.1 days per decade (*10*, *57*). A combination of climate warming and higher atmospheric CO_2 concentrations has extended the growing period of many plant populations (*58*). In a large global analysis, which included 21 phenological metrics such as leaf-off and leaf-on dates and growing season length, plant phenologies were found to have shifted by more than 2 standard deviations across 54% of the Earth's land area during the past three decades (*59*).

In marine and freshwater systems, advances in the timing of annual phytoplankton and diatom blooms, the basis for many aquatic food webs, have occurred more rapidly than temporal shifts in terrestrial plants (*37*, *60*). Such changes in plankton phenology have been attributed to increases in water temperatures, reduction in the duration of ice cover and the alteration of the seasonal duration of thermal stability or stratification of the water column.

Shifts in spawning times have been documented for 43 fish species in the north-east Pacific Ocean from 1951-2008, with earlier spawning associated with increased sea surface temperature and later spawning associated with delays in seasonal upwelling of nutrients towards the ocean surface (*61*). Similar impacts on breeding have been observed in terrestrial and marine bird species (*62*).

Changes in the timing of migration events have been extensively documented, including advances in spring arrival dates of long-distance migratory bird species in Europe, North America and Australia (*63–65*). Similarly, long-term data on many amphibians and mammals has shown advancements in spring and delays in autumn migration (*66–68*) and altered peak calling periods of male amphibians (*67–69*). In the largest meta-analysis to date of phenological drivers and trends among species in the southern hemisphere, 82% of terrestrial datasets and 42% of marine datasets demonstrated an advance in phenology associated with rising temperature (*70*).

Abundance and population dynamics

Acute temperature stress can have severe negative effects on population dynamics such as abundance, recruitment, age structure and sex ratios. Meta-analyses across thousands of species report that approximately 80% of communities across terrestrial, freshwater, and marine ecosystems exhibited a response in abundance that was in accordance with climate change predictions (*10*, *70*). In a meta-analysis on marine species, 52% of warm-adapted species increased in abundance, whereas 52% of cold-adapted species decreased (*71*). Temperature spikes may cause mass mortality of key ecosystem engineers in both temperate and tropical oceans. Excessive heat kills canopy-forming macroalgae in temperate marine systems (*72*) and causes bleaching and mass mortality of corals in the tropics (*73*). Reductions in sea ice extent have caused declines in abundances of ice-affiliated species in the Arctic (e.g. ivory gulls (*Pagophila eburnea*), ringed seals (*Pusa hispida*), and polar bears (*Ursus maritimus*) (*74*)) whereas, in some cases such as on Beaufort Island in the southern Ross Sea, the loss of ice from receding glaciers resulted in increased abundances of Adélie penguins (*Pygoscelis adeliae*) (*75*). In the United States, the bull trout (*Salvelinus confluentus*) has lost > 10% of its spawning grounds in central Idaho over the past 13 years due to increased water temperatures (*76*), while the brown trout (*Salmo trutta*) has lost habitat in the Swiss Alps (*77*). In western Canada, reduced survival of adult migrating Fraser River sockeye salmon (*Oncorhynchus nerka*) has been observed with increased water temperatures (*78*) and in eastern Canadian lakes, golden-brown algae dramatically increased in abundance as water temperature increased 1.5 °C during the latter part of the twentieth century (*79*). Some of the best evidence for climate-change impacts on the abundance of terrestrial species comes from analysis of bird population trends derived from systematic monitoring schemes in Europe, with warmth-adapted species having increased in abundance on average since the 1980s and cold-adapted species having declined (*80*).

Climate change can increase the abundance of temperature sensitive disease vectors, with subsequent effects on disease outbreaks. In the African Serengeti, there is some evidence that a combination of extreme weather, high abundances of ticks carrying *Babesia*-piroplasm and suppressed immunity to canine distemper virus led to widespread mortality of lions (*Panthera leo*) (*81*). In marine systems, field evidence shows corals are increasingly susceptible to white band disease at higher temperatures, leading to declines in two of the most important reef-building acroporid (branching) corals in the western Atlantic (*82*).

Species

Distribution

One of the most rapid responses observed for marine, freshwater, and terrestrial species is a shift in their distributions to track optimal habitat conditions (*71*, *83*, *84*). Across land and aquatic ecosystems, species have expanded their leading (cold limit) edge by 19.7 km per decade with marine species expanding by 72 km per decade compared to 6 km per decade in terrestrial species (*37*). The distributions of many marine taxa have shifted at higher velocities than those of terrestrial taxa (*37*) because areas with rapid changes in climate extend across broader regions of the ocean than on land, and connectivity in marine environments tends to be high (*85*). To illustrate this point, corals around Japan have shifted their range by up to 14 km per year over the past 80 years (*86*) and in waters off the south-east coast of Australia intertidal invertebrate species have shifted their geographic distributions polewards at an average rate of 29 km per decade (*87*). Where connectivity allows for dispersal, some freshwater fishes are capable of shifting at rates comparable to marine and terrestrial taxa (*88*), but mean shifts by river fishes in some regions have been insufficient to compensate for measured temperature rises (*89*).

There has been a consistent overall trend for tropical, warm-adapted species to expand their ranges into environments previously dominated by temperate cold-tolerant species (cf. “tropicalization” (*90*)). A similar phenomenon has been documented in the Arctic, where boreal fish communities have responded to warming in the Barents Sea by shifting northward, resulting in a high turnover in Arctic fish communities (cf. “borealization” (*91*)). Similarly, on land, increased minimum temperatures have driven rapid changes in the range size (as well as distribution) of Swedish birds, with northern species retracting and southern species expanding northwards (*92*).

In addition to latitudinal changes, many observed shifts in species distributions occur across elevation gradients. In the mountains of New Guinea, birds have shifted their distributions upslope by 95-152 m from 1965 to 2013 (*93*). A similar upslope shift was observed in recent decades in mountainous stream-dwelling fish in France (*89*), North American plants (*94*), and Bornean insects (*95*). An analogous response has been the shift to deeper, colder waters among some marine fishes (*91*).

In some cases species have shown no response or even downhill shifts in their distributions (*96*) or increased frequency of range disjunction rather than poleward or upward range shifts (*97*). Savage and Vellend (*98*) found upward range shifts in North American plant species and an overall trend towards biotic homogenization from 1970 to 2010, but their study also documents considerable time lags between warming and plant responses (also see (*99*, *100*). Delayed community responses to increasing temperature may be in part due to the buffering effects of microhabitats (*101*, *102*) and possibly moisture, which is a critical, but less often studied, driver in the redistribution of species (*103*). For example, Crimmins *et al.* (*104*) observed downhill movements for North American plants under climate change over an 80-year period, which they attribute to changes in water balance rather than temperature.

Community

Interspecific relationships

As a by-product of the redistribution of species in response to changing climate, existing interactions among species are disrupted and new interactions emerge (*105*, *106*). These novel biotic interactions can exacerbate the impacts of abiotic climate change (*107*, *108*). Woody plants are invading arctic and alpine herb-dominated communities in response to rapid warming in recent decades, leading to secondary shifts in distribution by other plants and animals (*92*). In the Sierra Nevada Mountains of California, Tingley and Beissinger (*109*) found high levels of avian community turnover during the past hundred years at the lowest and highest elevations and in Greece, Sgardeli *et al.* found similar patterns of temperature driven turnover in butterfly communities (*110*). There are surprisingly few studies of observed impacts of climate change on competitive interactions (*108*). In one example from Sweden, Wittwer *et al.* (*111*) found that of the four bird species occupying the same ecological guild, resident birds were able to adapt to warmer temperatures and out compete the sole long-distance migrant, *Ficedula hypoleuca*.

New interactions among species can also lead to trophic disruptions such as overgrazing. In western Australia, for example, overgrazing of subtropical reefs by the poleward spread of tropical browsing fish has suppressed recovery of seaweeds following temperature-induced mortality (*112*). These types of trophic disruptions are escalating, with range shifts by tropical herbivorous fishes increasing herbivory rates in subtropical and temperate coastal ecosystems where seaweeds are the dominant habitat-forming taxa (*90*).

Phenological mismatches have been observed between butterflies and their annual host plants, with the plants dying before the insect larvae were ready to enter diapause (*113*). Similarly, an analysis of 27 years of predator-prey data from the UK showed asynchronous shifts between the tawny owl *Strix aluco* and its principle prey, the field vole (*Microtus agrestis*), which led to reduced owl fledging success (*114*). In Lake Washington, United States, spring diatom blooms advanced by over 20 days since 1962, resulting in predator-prey mismatches with their main grazer, the water flea *Daphnia pulicaria* and population declines in the latter (*60*). In Canadian arctic lakes, asynchronous shifts in diatom blooms resulted in generalist water fleas being replaced by more specialist species (*115*). At higher trophic levels, warming has affected the fry and the juvenile life-history stages of lake char (*Salvelinus umbla*) via direct impacts on their zooplankton and vendace (*Coregonus alba*) food sources (*116*).

Productivity

Changes in productivity are one of the most critical impacts of climate change across aquatic and terrestrial ecosystems (*117*, *118*). In marine systems, climate-mediated changes in chlorophyll-a concentrations as a proxy of phytoplankton biomass have been highly variable (*119*). Depending on location, these include both dramatic increases and decreases in abundance as well as changes in phenology and distribution of phytoplankton over the past several decades. In a global study of phytoplankton since 1899, an approximate 1% decline in global median phytoplankton per year was strongly correlated with increases in sea-surface temperature (*120*), whereas in the Antarctic Peninsula, phytoplankton increased by 66% in southern subregions and decreased by

12% in northern subregions over a 30 year period. These conflicting observations in the Antarctic are in part linked to changes in sea-surface temperature but also changes in ice cover, cloudiness, and windiness affecting water-column mixing (*121*).

In deep tropical freshwater lakes dominated by internal nutrient loading through regular mixing, warmer surface waters confer greater thermal stability, with reduced mixing and return of nutrients to the photic zone, substantially decreasing primary productivity (*122*), phytoplankton growth (*123*) and fish abundance (*122*). In contrast, eutrophication effects are exacerbated by higher temperatures in shallow lakes, resulting in increased productivity and phytoplankton and toxic cyanobacteria blooms (*124*).

Globally, terrestrial plant growth has increased with increasing temperatures and CO_2 levels. This may in part explain the on average 6% increase in net primary productivity (NPP) from 1982 to 1999 (*125*), although these changes in NPP may also be related to natural variation in El Niño-La Niña cycles (*126*). However, responses are highly variable and some terrestrial systems are not experiencing increased productivity due to either extreme temperatures or lack of water. Severe short-term droughts in climatically stable rainforest environments are unusual, but in recent years have increased in frequency. These events have led to changes in forest canopy structure in Amazonia (*127*) and decreases in above-ground woody and leaf biomass in the Congo basin (*128*). Across large expanses of the Amazon, there has been an overall reduction in above-ground biomass owing to increased climate variability over the past three decades (*129*).

Impacts across ecosystems

All three biotic realms (terrestrial, freshwater, marine) are being impacted by climate change, and the evidence summarized here reveals that these impacts span the biological hierarchy from genes to communities. Of the 94 processes considered, we found that 82% have evidence of impact by climate change, and this has occurred with just 1 °C of average warming globally (Fig. 1). Impacts range from genetic and physiological changes to responses in population abundance and distribution (Fig. 2).

The fact that evidence is missing for some processes is more likely to reflect data deficiencies than the absence of any response to climate change. We only considered field-based case studies that report changes in the processes through time. Importantly, for many components, such as genetics (*23*) and physiology (*29*), there is strong evidence from experiments on a wide range of species that individuals and populations can and likely will respond to climate change. Thus, even though we found compelling evidence of widespread responses across the biological hierarchy, we still consider our discussion of impacted processes to be conservative. To illustrate this point, Box 1 shows the range of observed responses in the water flea *Daphnia*, which spans the entire hierarchy of biological organization.

Ecosystem state shifts

As ecological systems continue to accumulate stress through compromised ecological processes either directly from climate change or interactively with other forced disturbances (see Supplement Material for discussion), diminished resilience may lead to ecological regime shifts —where one ecosystem state shifts to an alternative and potentially undesirable stable state. For example, some reefs are transitioning from coral- to algal-dominated states as a consequence of mass coral mortality (*130*) while kelp forests are turning into rocky barrens in temperate seas (*90*, *131*, *132*). In lakes, climate change has increased the risk of regime shifts from clear-water to turbid states and increased the occurrence of cyanobacteria blooms (*124*). If sufficient community-based processes are impacted at regional scales, wholesale biome shifts can occur such as has been observed in Alaska where tundra is transitioning to boreal conditions (*133*). These are clear signs of large-scale ecosystem change and disruption, where disequilibrium rapidly pushes the system into a new state (*134*).

Using ecology to better understand climate change impacts on human well-being

Threats to production

The impacts of climate change on marine fisheries have major consequences for human societies since these currently provide ~17% of the global protein for people (*135*). There is, however, no current consensus on the costs and benefits of the on-going global redistribution of fisheries, because trends are highly variable. In the Arctic, commercially important fish, such as Atlantic cod (*Gadus morhua*) and walleye pollock (*Theragra chalcogramma*), have increased in biomass primarily due to increases in plankton production from reduced sea ice (*136*, *137*), whereas changes in fish biomass in the Southern Ocean are less clear (*138*). In Switzerland, which has experienced twice the average global temperature increase, trout catches have been halved over two decades due to rising temperatures in Alpine streams (*77*).

Changes in total marine productivity are not just attributed to abundance shifts but also morphological shifts. Indeed, some fish species appear to be shrinking but attributing this solely to ocean warming is difficult because size-dependent responses can be triggered by commercial fishing as well as long-term climate change (*139*). However, long-term trend analyses show convincingly that eight commercial fish in the North Sea underwent simultaneous reductions in body size over a 40-year period due to ocean warming, resulting in 23% lower yields (*140*). Reduced body size in fish is also being recorded in lakes and rivers throughout Europe, and has been linked to increased temperature and climate-induced shifts in nutrient inputs (*141*, *142*).

Impacts on plant genetics and physiology are influencing human agricultural systems. For example, yields in rice, maize, and coffee have declined in response to the combined effects of rising temperatures and increasing precipitation variability in the past decades (*143–145*). Genetics is being used to counteract decreasing yields in some key crops such as wheat (for which globally, yields have declined by 6% since the early 1980s (*146*)), through crossing domesticated crops with wild relatives to maintain the evolutionary potential of varieties (*147*). Yet, some important wild strains are also showing signs of impact from climate change. Nevo *et al.* (*148*) documented high levels of genetic changes in the progenitors of cultivated wheat and barley in Israel over the last 28 years. These wild cereals exhibited landscape-level changes in flowering time and a loss of genetic diversity in response to increasing temperatures.

Losing genetic resources in nature may undermine future development of novel crop varieties (*149*) and compromise key strategies that humans use to adapt to climate change. One such strategy is to use assisted gene flow, the managed movement of individuals or gametes between populations to mitigate local maladaptation in the short and long term (*150*). Where genetic introgression, the movement of genetic material from one species into the genome of another, can occur from unexploited natural populations to managed or exploited populations that are poorly adapted to warmer or drier conditions, adaptive changes may be facilitated (*151*), as in white spruce (*Picea glauca*), a tree commonly harvested for timber (*152*). Human-assisted evolution may also be a key strategy in maintaining reef-dependent fisheries by accelerating and enhancing the stress tolerance of corals (*153*).

Phenological changes due to milder winters are influencing crop and fruit production (*154*). Climate change has reduced winter chill events in temperate agricultural areas (*155*), which can desynchronize male and female flowers and trigger delayed pollination, delayed foliation, and reduced fruit yield and quality. To counter this, tree crop industries have developed adaptation measures such as low-chill cultivars with dormancy-breaking chemicals. For example, the ‘UFBest’ peach requires four times fewer chill days than cultivars from more temperate climates (*156*). Advances in the timing of budding, flowering and fruiting of plant species has induced earlier harvesting periods in some countries (e.g. Japan, (*157*)).

Pollination is a key process linked to yields for a large number of crops. The short-lived, highly mobile insect species that provide pollination services to numerous crops have responded rapidly to changing climates by shifting their ranges throughout North America and Europe (*158*). Additionally, over the past 120 years, many plant-pollinator networks have been lost with overall decline in pollination services, which is attributed to a combination of habitat loss and climate warming (*159*). Yet, observed changes in the phenology, abundance and distribution of common pollinators have not been directly linked to declines in yields of animal-pollinated crops. This is likely due to limited data that directly link pollination services to crop yield over time and may, in part, reflect resilience provided by the diversity of insect species that pollinate many crops (*160*, *161*). More specialized pollination systems are expected to be more vulnerable to climate change. Humans have adapted to the declines in native pollinators by transporting domesticated pollinators to crop locations.

Pest and disease threats

Climate-induced ecosystem-level changes, such as forest die-offs, have an obvious impact on people, with a reduction in timber supplies and carbon sequestration, and changes in water quality and watershed volume (*162–164*). Several native insect species from North America, with no prior records of severe infestation, have recently emerged as severe pathogens of forest resources due to changes in population dynamics. These include the Aspen leaf miner (*Phyllocnistis populiella*), the leafblotch miner (*Micrurapteryx salicifoliella*) and the Janet’s looper (*Nepytia janetae*), which have decimated millions of hectares of aspen, willows, and spruce-fir forests since the early

1990s (*165*). Known pests such as mountain and southern pine beetles (*Dendroctonus frontalis* and *D. ponderosae*, respectively) and spruce beetles (*D. rufipennis*), have recently expanded their distribution and infestation intensity on commercially important pine and spruce trees (*162*, *165*). These outbreaks may increase in the future as hundreds of plant pest and pathogen species have shifted their distributions 2-3.5 km yr^{-1} poleward since the 1960s (*166*).

An emerging threat to human health under climate change is vector-borne diseases (*167*). Vectors that have shifted their ranges and abundance can be found in marine, freshwater, and terrestrial systems. For example, in marine systems, unprecedented warming in the Baltic Sea led to emergence of *Vibrio* infections in Northern Europe (*168*, *169*), a geographic locality that had limited prior occurrence of this waterborne bacterial pathogen. Mosquitoes (e.g., *Aedes japonicas, A. aegypti, A. albopictus)* are extending their distribution into areas that are much warmer than their original habitats. As a result of ecological adaptation, mosquitos have become more competent vectors for spreading diseases such as chikungunya, dengue, and possibly the emerging Zika virus (*170*). Lastly, in terrestrial systems, Levi *et al.* (*171*) found that the nymph stage of the Lyme disease-carrying blacklegged tick, *Ixodes scapularis*, exhibited an overall advancement in nymph and larvae phenology since 1994, shifting the timing of greatest risk for pathogen transfer to humans to earlier in the year.

Losing intact ecosystems and their function

Changes in ecological processes might compromise the functionality of ecosystems. This is an important consideration because healthy systems (both terrestrial and marine) sequester substantial amounts of carbon (*172*), regulate local climate regimes (*173*), and reduce risks associated with climate-related hazards such as floods, sea-level rise and cyclones (*174*). In island and coastal communities, coral reefs can reduce wave energy by an average of 97% (*175*) and coastal ecosystems such as mangroves and tidal marshes buffer storms (*176*), while on land intact native forests are important in reducing the frequency and severity of floods (*177*). In many cases, maintaining functioning systems offers more sustainable, cost-effective and ecologically sound alternatives than conventional engineering solutions (*16*).

Science and action in a warmer world

The United Nations Framework Convention on Climate Change (UNFCCC) and the recent COP21 agreement in Paris presently offer the best opportunity for decisive action to reduce the current trajectory of climate change. This agreement set global warming targets of 1.5-2°C above pre-industrial levels in order to avoid "dangerous climate change", yet the current 1°C average increase has already had broad and worrying impacts on natural systems, with accumulating consequences for people (Table 1). Minimizing the impacts of climate change on core ecological processes must now be a key policy priority for all nations, given the adoption of the UN Sustainable Development Goals aiming to increase human well-being. This will require continued funding of basic science focused on understanding how ecological processes are interacting with climate change, and of programs aimed at supporting ecosystem-based adaptations that enhance natural defences against climate hazards for people and nature, and ensures on-going provision of natural goods and services (*178*).

It also means recognizing the role that intact natural ecosystems, particularly large areas, play in overcoming the challenges that climate change presents, not only as important repositories for carbon, but also because of their ability to buffer and regulate local climate regimes and help human populations adapt to climate change (*16*, *174*). These systems are also critical for maintaining global biodiversity, as the connectivity provided by large, contiguous areas spanning environmental gradients, such as altitude, depth or salinity, will maximize the potential for gene flow and genetic adaptation, while also allowing species to track shifting climates in space (*179*).

The overriding priority of the UNFCCC is to set in motion a sustained global reduction in greenhouse gas emissions. This must be achieved alongside an improvement in our understanding of key ecological processes that form the foundation to biological and human systems, and in tandem with efforts to conserve the natural habitats in which such ecological processes operate. It is now up to national governments to make good on the promises they made in Paris through regular tightening of emission targets, and also to recognize the importance of healthy ecosystems in times of unprecedented change (*180*). Time is running out for a globally synchronized response to climate change that integrates adequate protection of biodiversity and ecosystem services.

Table. 1 **Climate change consequences for humans.** Impacted ecological processes have direct consequences in food systems and human health.

	Organism	**Population**	**Species**	**Community**
	Genetics, Physiology, Morphology	**Phenology, Dynamics**	**Distribution**	**Interspecific relationships, Productivity**
Resource security	Rapid genetic adaptation to climate change in timber species	Increased herbivory on crops and timber by pests	Overall distribution shifts in marine and freshwater fisheries	Decline in plant-pollinator networks and pollination services
	Decreased crop yields in hot climates and increases in cool climates	Decreased genetic diversity and altered flowering time in wild cereals and novel crop varieties	Reduced range size or changes in pollinator abundance	Novel pests and invasive species
	Increased weed-crop competition and parasite-livestock interactions	Reduced fruit yields from fewer winter chill events		
	Decreased yield in fisheries from reduced body size	Reduced productivity in commercial fisheries		
Human health	Decline in reef calcifiers threatens coastal communities—loss of protection from storm surges and loss of food/protein sources	Increased costs and risk to subsistence communities from loss of sea ice and permafrost	Expanding and/or new distributions of disease vectors	Increased human-wildlife conflicts

	Rapid adaptation of disease vectors to new climatic conditions	Redistribution of arable land	Novel disease vectors

Summary figure legend:

Climate change impacts on ecological processes in marine, terrestrial and freshwater ecosystems.
Impacts can be measured on multiple processes at different levels of biological organization within ecosystems. In total, 82% of 94 ecological processes show evidence of being impacted by climate change. Within levels of organization, the percentage of processes impacted varies from 60% for genetics to 100% for species distribution.

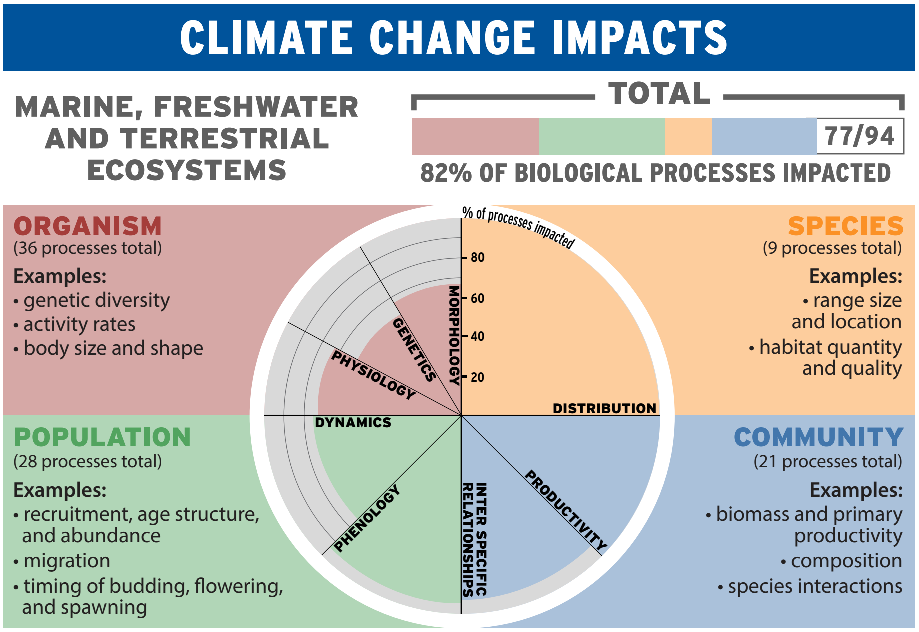
Figure 1 Climate change impacts on Earth's marine, terrestrial and freshwater systems.
The presence of observed impacts on the different levels of biological organization and its inner components across the Earth's marine, terrestrial and freshwater ecosystems. The denominator represents the total number of processes that we considered for each group and the numerator is the number of these processes with evidence of impact (see Fig. S1 and Table S1 for a complete list of processes). In total, 82% of all ecological processes (n=94) considered have observed evidence of impact by climate change. Each process has at least one supporting case study. The * indicates whether the impacted process was assessed in a meta-analysis in addition to case studies. Thus, two stars (**) indicate that two processes were assessed in at least one meta-analysis. Confidence that the observed impact can be attributed to climate change was assigned for each level of organization and ranges from very low, low, medium, high to very high; this assessment is based on tables 18-7, 18-8, and 18-11 in (*13*)). The darkest circle indicates confidence

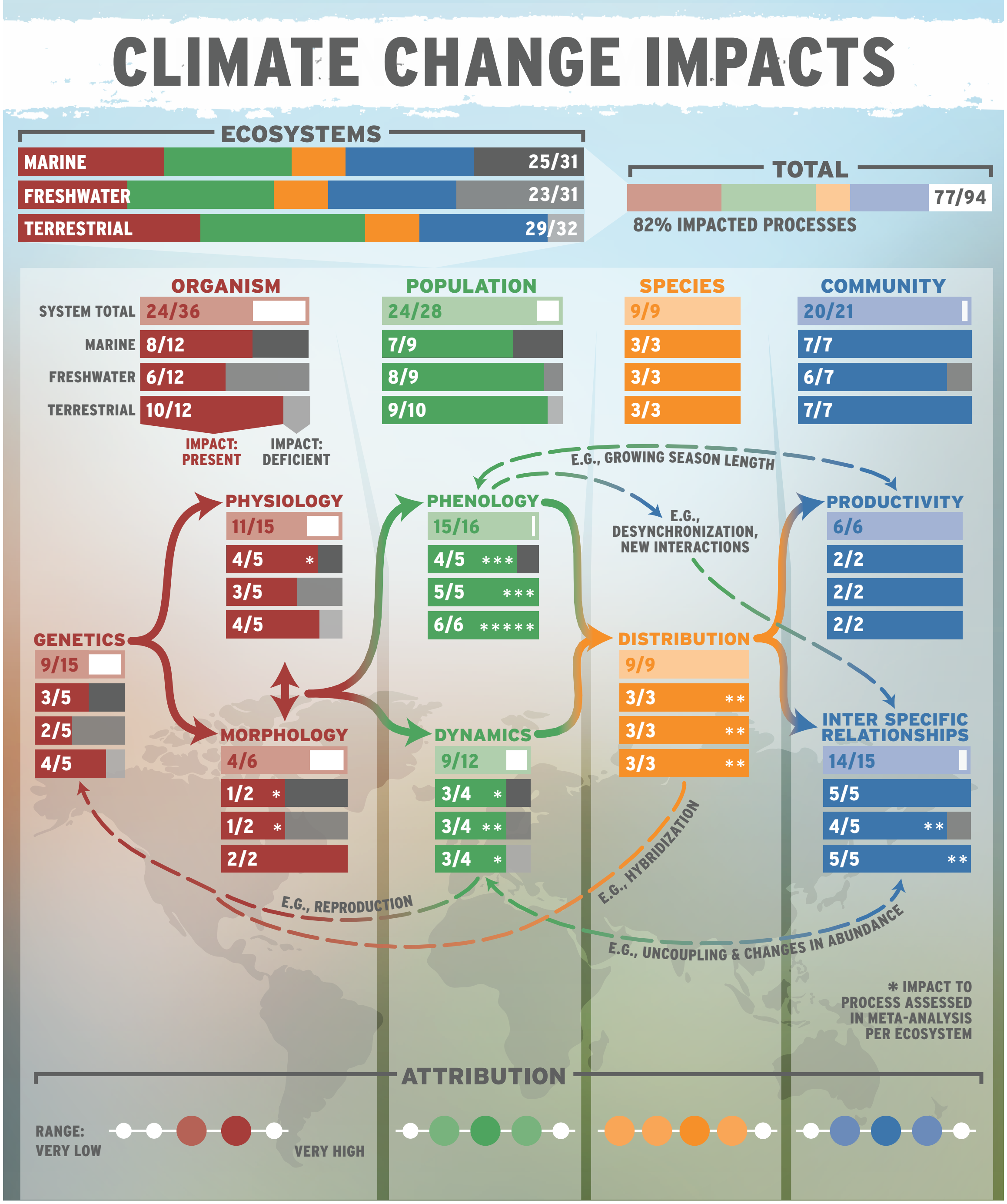
level with the most literature support. (image credit: Stacey Jones/ Michele Wood/IFAS)

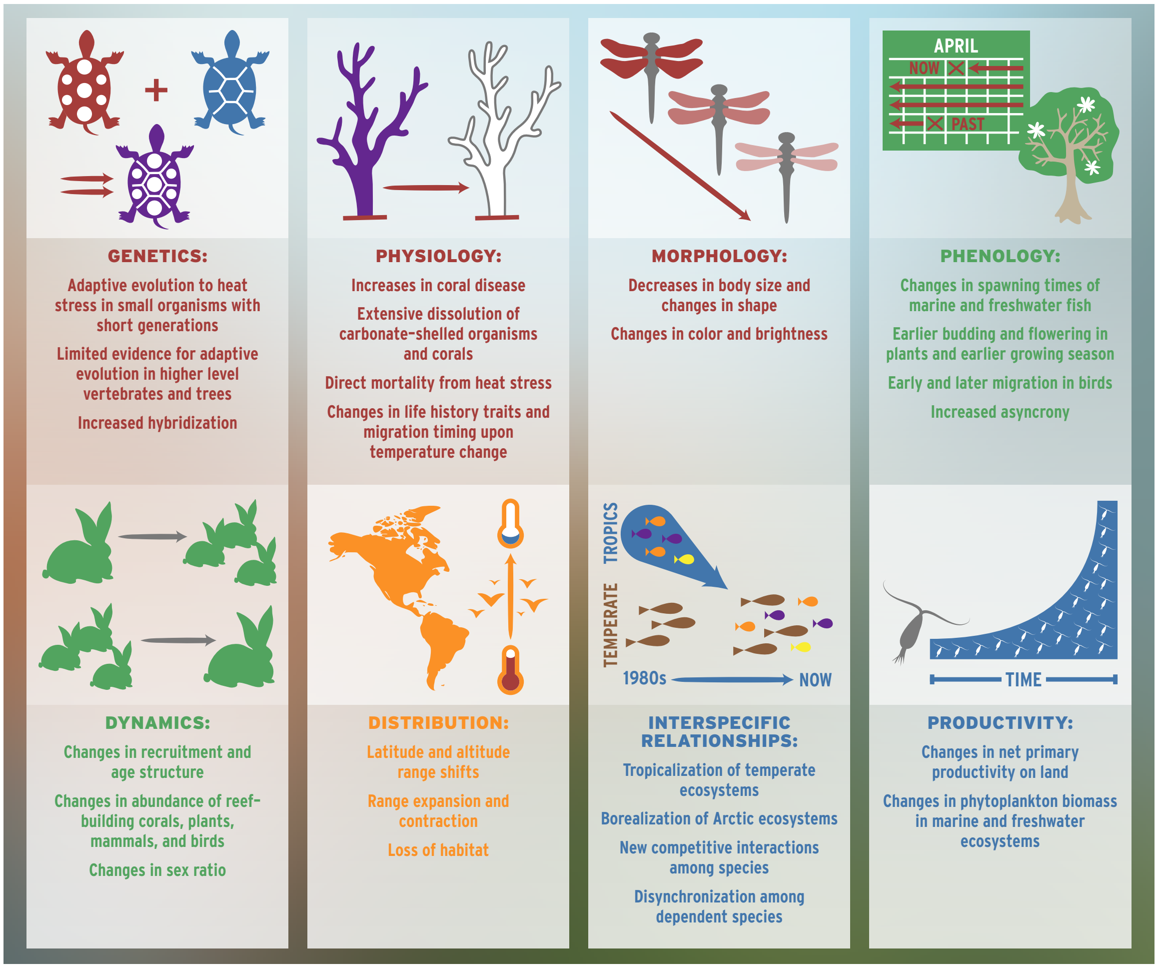
Figure 2 Climate impacts on ecological processes.

Examples of ecological components and processes impacted by climate changes across marine, terrestrial and freshwater ecosystems (see Fig. S1 and Table S1). (image credit: Stacey Jones/Michele Wood/IFAS)

Box 1. A complete hierarchy of climate change impact in one model system – the water flea *Daphnia*. Combining time-series data with experimental approaches can lend insights to the breadth of climate change impacts. For water fleas of the genus *Daphnia* (Fig. 3), for instance, there is evidence for responses to temperature at all levels of biological organization. *Daphnia* are important grazers in lakes and ponds (*181*). They adapt to temperature increase by genetic changes in thermal tolerance (*18*), body size and life history traits (*182*, *183*). In the laboratory, *Daphnia* exhibit phenotypic plasticity in physiology to changing temperatures (e.g. hemoglobin quality and quantity, (*184*); metabolic activity, (*185*)), behaviour (swimming activity, (*185*)), life history traits (*186*), and body size (*183*). *Daphnia* adjust their phenology (*187*) and abundance (*188*) in response to increases in temperature, which results in mismatches with phytoplankton dynamics (*60*). Warmer, drier weather over two decades can lead to expanded distributions and increased colonization capacity (*189*). Temperature influences interactions of *Daphnia* with predators (*190*) and parasites (*191*), and adaptation to increased temperature influences competitive strength (*186*). In the absence of fish, high abundances of *Daphnia* in +4°C heated mesocosms exert strong top-down control on phytoplankton (*192*).




CLIMATE CHANGE IMPACTS
ECOSYSTEMS
MARINE
25/31
FRESHWATER
23/31
TERRESTRIAL
29/32
TOTAL
77/94
82% IMPACTED PROCESSES
ORGANISM
POPULATION
SPECIES
COMMUNITY
SYSTEM TOTAL
24/36
24/28
9/9
20/21
MARINE
8/12
7/9
3/3
7/7
FRESHWATER
6/12
8/9
3/3
6/7
TERRESTRIAL
10/12
9/10
3/3
7/7
IMPACT: PRESENT
IMPACT: DEFICIENT
E.G., GROWING SEASON LENGTH
PHYSIOLOGY
11/15
4/5 *
3/5
4/5
PHENOLOGY
15/16
4/5 ***
5/5 ***
6/6 *****
E.G., DESYNCHRONIZATION, NEW INTERACTIONS
PRODUCTIVITY
6/6
2/2
2/2
2/2
GENETICS
9/15
3/5
2/5
4/5
DISTRIBUTION
9/9
3/3 **
3/3 **
3/3 **
MORPHOLOGY
4/6
1/2 *
1/2 *
2/2
DYNAMICS
9/12
3/4 *
3/4 **
3/4 *
INTER SPECIFIC RELATIONSHIPS
14/15
5/5
4/5 **
5/5 **
E.G., HYBRIDIZATION
E.G., REPRODUCTION
E.G., UNCOUPLING & CHANGES IN ABUNDANCE
* IMPACT TO PROCESS ASSESSED IN META-ANALYSIS PER ECOSYSTEM
ATTRIBUTION
RANGE:
VERY LOW
VERY HIGH



GENETICS:

Adaptive evolution to heat stress in small organisms with short generations

Limited evidence for adaptive evolution in higher level vertebrates and trees

Increased hybridization

PHYSIOLOGY:

Increases in coral disease

Extensive dissolution of carbonate-shelled organisms and corals

Direct mortality from heat stress

Changes in life history traits and migration timing upon temperature change

MORPHOLOGY:

Decreases in body size and changes in shape

Changes in color and brightness

PHENOLOGY:

Changes in spawning times of marine and freshwater fish

Earlier budding and flowering in plants and earlier growing season

Early and later migration in birds

Increased asyncrony

DYNAMICS:

Changes in recruitment and age structure

Changes in abundance of reef-building corals, plants, mammals, and birds

Changes in sex ratio

DISTRIBUTION:

Latitude and altitude range shifts

Range expansion and contraction

Loss of habitat

INTERSPECIFIC RELATIONSHIPS:

Tropicalization of temperate ecosystems

Borealization of Arctic ecosystems

New competitive interactions among species

Disynchronization among dependent species

PRODUCTIVITY:

Changes in net primary productivity on land

Changes in phytoplankton biomass in marine and freshwater ecosystems

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Acknowledgements: We thank the IPCC, IPBES and the thousands of researchers that have studied biodiversity and ecosystem services and the impacts of climate change, on the Earth—many of which we were not able to cite due to length restrictions of the journal. Sasha Greenspan, Joel Greenspan, and Edward Perry provided helpful discussion and feedback on this manuscript. Stacey Jones and Michele Wood were instrumental in figure creation. LDM acknowledges KU Leuven Research Fund PF/2010/07 and Future Earth core project BioGENESIS. We thank the IUCN Climate Change Specialist Group for collaborative discussions on climate change themes and impacts on conservation of species and ecosystems and three anonymous reviewers for constructive suggestions that improved our manuscript.

Supplemental Material Section

Supplement material (SM) expands on the review search criteria, provides a discussion on interactive and cumulative effects of climate change and direct impacts of climate change on people, and a compilation of evidence of climate change impact on ecological processes. SM contains additional references (*193-313*)

Supplemental Section

This supplement material expands on the review search criteria, provides a discussion on interactive and cumulative effects of climate change and direct impacts of climate change on people, and a compilation of evidence of climate change impact on ecological processes.

Literature review criteria

We used ISI Web of Knowledge and Google Scholar to conduct our literature search. Keywords were selected to identify studies on climate change (climate change*, global warming*, sea-level rise*, extreme weather*, drought*, CO2 concentration*) and observed impacts on ecological processes (hybridization*, population reduction*, range size*, turnover*, etc; see full list of components and ecological processes in Table S1) within the three ecological realms (marine*, terrestrial*, freshwater*). We also screened the literature cited in the resulting papers in order to identify other published papers on climate change impacts. We focused on post-2012 literature, but if no published literature pertaining to this 3-year period was found we extended our search to include earlier studies. We did not list all relevant literature but rather screened for studies that met our criteria and featured representative papers in terms of both observed responses and temporal scales, avoiding redundancy.

We illustrate impacts for the broad set of core ecological processes by referring to case studies reporting such effects in the wild. These case studies refer to a wide range of organism groups and systems in the three major biomes (marine, terrestrial, freshwater). We considered case studies that report responses in the wild through time, either through monitoring the changes or, in a few cases, resurrection experiments, where stored seeds or eggs from past climate were resurrected to analyse trait change (e.g., (*193*)). We focused on post-2012 literature in order to capture the most recent and relevant studies. We critically assessed the evidence in order to ensure that we included only those studies in which the authors provide convincing evidence for climate change as the main or key driver of the observed ecological responses. Additionally, we used existing meta-analyses that collate responses for single or multiple ecological processes across multiple studies to provide additional support in assessing impacted processes (see Figure S1). It is inherently difficult to attribute a biological change to a specific driver in the multidimensional context of natural systems, which are intrinsically complex and context-dependent, not only in terms of physical and chemical characteristics but also with respect to biotic interactions (see (*113*, *194*)). In this assessment, experimental or space-for-time studies that show an observed response could be induced by climate change were not systematically cited but were in some cases used when they provided additional support for the link to climate change.

Other Considerations

Interactive and cumulative effects

Our synthesis focuses on the direct effects of increasing temperature and climate variability on ecological processes. However, these processes are often interacting with other stressors including habitat loss and fragmentation, exploitation, invasion by exotic species, eutrophication and pollution. Evidence of the interactive and cumulative effects of climate change with these other stressors is accumulating. In a global meta-analysis of 1319 papers, Mantyka-Pringle *et al.* (*195*) found that the most important determinant of habitat loss and fragmentation effects, averaged across species and geographic regions, was current maximum temperature, followed by mean precipitation change over the last 100 years. Habitat loss and fragmentation effects were greatest in areas with high maximum temperatures. Conversely, negative effects were lowest in areas where average rainfall had increased over time. In an example that straddles both the freshwater and marine environments, the recent dramatic decline of Canada's Fraser River sockeye salmon populations has been attributed to the cumulative and interactive effects of climate change impacts in both its freshwater and marine environments, along with viral and/or bacterial pathogens, exploitation and habitat loss and degradation (*196*). In a meta-analysis of 171 marine studies that examined impacts of multiple stressors, climate variables (temperature, CO_2, UV) often interacted with non-climate stressors such as salinity, nutrients, toxins, and fishing pressure (*197*). This research suggests that as our understanding of interactive and cumulative effects improves we are likely to discover many more examples where the addition of climate change on systems already under stress often leads to synergistic cumulative effects (*198*).

Direct Impacts on Humans

The direct impacts of climate change on humans are similar in many ways to climate change impacts observed on other species in nature. Direct impacts of climate-related extremes include changes in food production and water supply, damage to infrastructure and homes, and consequences for human health. These direct human impacts of climate change have been felt across nations at all levels of development (*199*): from the low-lying Pacific island nation states of Tuvalu and Kiribati on the forefront of sea level rise

(*200*), to increased frequency and intensity of cyclones at more southern and northern latitudes, which can lead to significant loss of life and financial damage (*201*), to rural Australia, where intense drought combined with record-high temperatures and strong winds in 2009 led to its most deadly bushfire in history with 173 fatalities and the destruction of more than 2000 homes (*202*). The degree of sea-level rise and storm surges being experienced by Pacific islands, increased severity of hurricanes in regions such as the United States and severe fires experienced in Australia are all consistent with climate change forecasts (*203–205*).

Table S1. Examples of observed biological responses to climate change in marine, terrestrial and freshwater systems. We provide evidence that these impacts have consequences for people. Some studies are appropriate for multiple processes but efforts were made to limit examples to one study per component and processes.

Component: Processes	**Marine**	**Terrestrial**	**Freshwater**	**Consequences for People**
Genetics: **Changes in genetic diversity** **Genetic adaptation to abiotic changes** **Genetic adaptation to biotic changes** **Hybridization and hybrid zones** **Landscape genetic patterns**	Changes in allelic diversity and heterozygosity in seal populations (*206*) Distributional shifts in response to rapid warming led to hybridization between two coastal fish species (*28*)	Natural selection on flowering time (*19*) Shifting hybrid zones between chickadee bird species (*25*) and flying squirrel species (*26*) Changes in genetic patterns and diversity across landscapes in an alpine mammal (*207*) Genetic responses in plants to climate change (*193*, *208*) Loss of adaptive genetic variation in the brown argus butterfly associated with climate-driven range shift (*209*) Changes in flowering and high turnover in simple sequence alleles from increased temperatures (*148*) Genetic adaptation of egg hatching in the winter moth Operophterra brumata to match oak bud burst (*210*) Relaxed selection from reduced freezing events triggered significant increase in freezing-sensitive phenolic chemotypes (*211*) The latitudinal cline in the alcohol dehydrogenase polymorphism of *Drosophila melanogaster* has shifted poleward (*212*)	Phenological adaptation in mosquitoes and water striders (*21*, *213*, *214*) Increased thermal tolerance (*18*) Increased hybridization between trout species (*27*)	Adaptation of exploited populations to climate change (*215*) Introgression of climate adapted genotypes into managed populations (*152*) Adaptation of human disease vectors to warming conditions (*170*) Changes in flowering and high turnover in simple sequence alleles from increased temperatures for important wild cereals (*148*) Rapid adaptation in commercially valuable tree (*216*)
Physiology: **Impact on activity**	Meta-analysis- (*12*) High sea temperatures	Increases in thermal and drought resistance as a consequence of	Life history traits, survival and anoxia stress in fish –	Declines in the US Pacific oyster industry due to unfavourable

rates (e.g., metabolism, performance, activity, etc) **Sex determination** **Disease susceptibility** **Life history traits (capacity to deal with stresses associated with climate change such as acidification (marine), anoxia (marine/freshwater), and drought (terrestrial/freshwater)** **Survival**	driving increase in coral disease susceptibility (*82*) Changes in sex ratios in snake pipefish (*31*) Extensive dissolution in pteropods due to OA (*40*, *41*) Changes in growth rates of marine fish in Tasman Seas (*217*) Increased coral calcification rates at high latitudes (*218*), decline in calcification at high temperatures (*219*)	adaptive plasticity (*220*) Changes in sex ratios of turtles (*34*) Direct mortality from extreme heat (cockatoos and flying foxes) (*221*, *222*) Drought induced mortality of trees (*223*, *224*) Increased disease susceptibility in birds (*225*)	correlation studies from long term data (Reviewed in (*226*))	carbonate conditions impacting on larval development (*227*) The number of heat related deaths in Europe increased by 8 - 34 % from 1990 to 2004, depending on the region (*228*) Decreased food production due to tolerance thresholds being exceeded in crops and livestock (*229*)
Morphology: Changes in body size and shape (including shell deposition and morphology) Changes in color and brightness	Meta-analysis – (*141*) Reduced body size (*140*) Decreased body size in marine communities (*141*) Climate induced changes in body size at species and community level in copepods (*230*) Ocean acidification from climate change causes dissolution of shells in mussels (*40*) and pteropods (*41*)	Due to metabolic processes, increased temperature has reduced body sizes (*44*, *45*) and also see (*42*) but in some scenarios has caused increased body size in cold environments (*42*, *47*) Reduced leaf area (*49*) Color changes in birds, butterflies, dragonflies (*50*, *51*, *231*) Pronounced changes in skull shape in alpine chipmunk (*Tamias alpinus*) (*54*).	Meta-analysis – (*141*) Reduced body size in fish, zooplankton, and phytoplankton (*141*, *232*) Shortened, warmer winters result in smaller eggs and larvae in cold-adapted lake fish (*233*) Increased temperature results in decreased body size in zooplankton (*234*)	Smaller fisheries yields from reduces body size (*140*)
Phenology: **Migration (departure / arrival)** **Budding and flowering** **Growing season length**	Meta-analyses- (*37*, *55*, *235*, *236*) Advances in timing and duration of spring phytoplankton blooms	Meta-analyses- (*10*, *55*, *70*, *236*, *57*, *239–242*) Advances in birth date (*47*, *243*) Earlier spring migration	Meta-analyses- (*55*, *70*, *236*) Altered peak calling periods for male frogs attempting to attract	Asynchronous harvests and changes in yields of commercial crops and fruits (*154*, *157*) Reduced winter chill events leads to desynchronization of

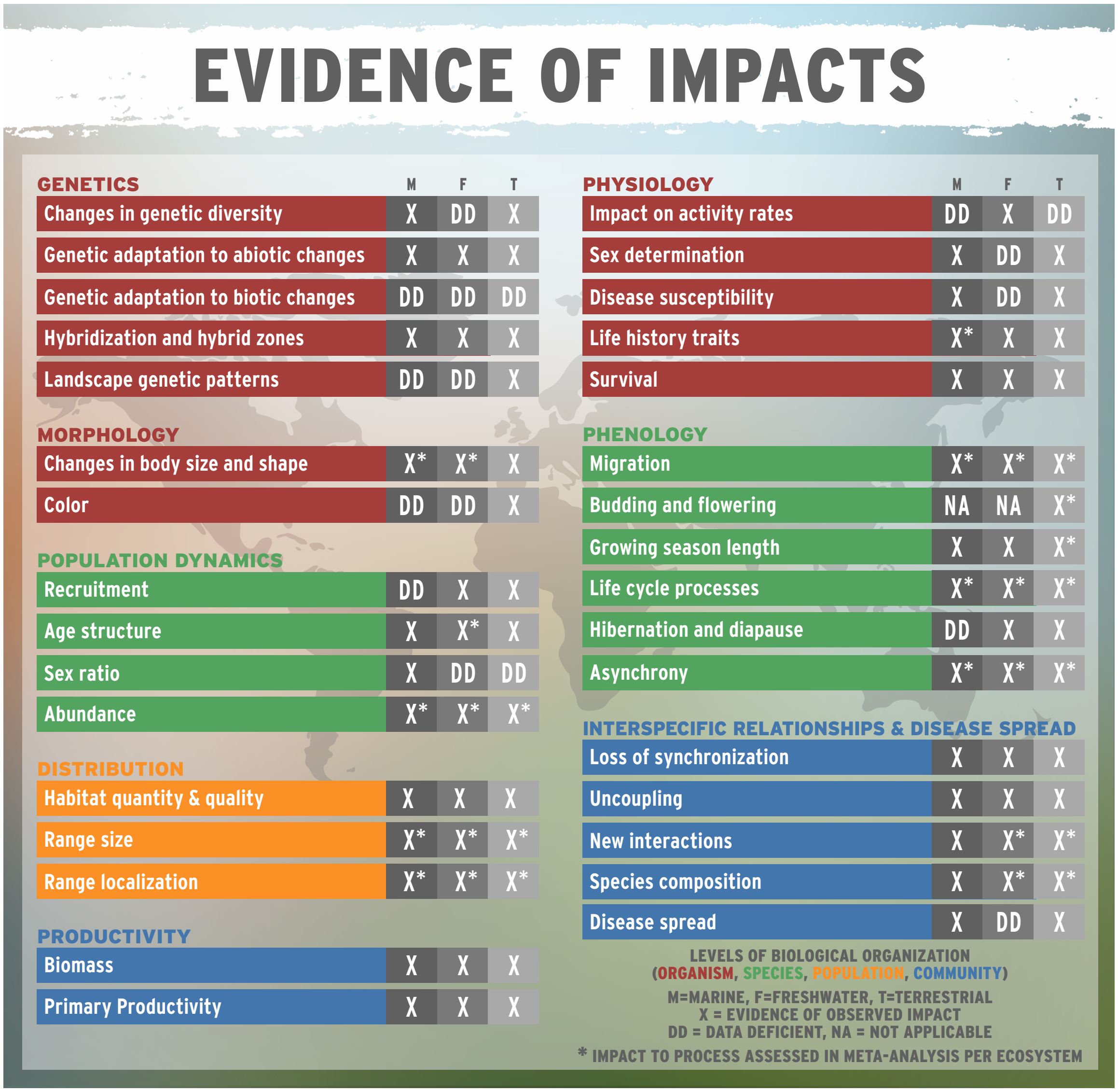
Life cycle processes (e.g., hatching, fledging, dispersal, fecundity) **Hibernation and diapause**	(*237*) Seasonal shifts in baleen whale movements (*66*) Shifts in fish spawning times (*61*) Reduction in coral fecundity following thermal stress (*238*)	arrival at nesting sites in birds (*63–65*) and delayed autumn migration (*244–246*) Advancement in spring migrations in vertebrates (*64*, *65*, *247*) Accelerated budding and flowering (*157*, *248*, *249*) and earlier growing season (*250*) Advancement of egg laying and changes in clutch size in birds (*62*) Reduction in fledging success in tawny owl from shift in main prey (*114*) Delayed and advanced hibernation (*251*, *252*) Phenological mismatch between butterfly larvae and host plant (*113*)	mates (*67–69*) Meta-analysis on phonological shifts by (*10*, *57*) Advancement of phytoplankton and diatom blooms (*60*) Phytoplankton phenology shifts attributed to changes in onset and duration of lake stratification, earlier ice-break up and warmer temperatures (*124*, *253*, *254*) Temperature-driven increases in diatom growth rates lead to an earlier onset of silica limitation in temperate lakes (*255*) Impacted life-cycle in fish through loss of food sources (*116*) Shifts (both delays and advancement) in reproductive timing in amphibian communities (*67*, *69*) Changes in the phenology and abundances of rotifer species resulting in a reduced niche overlap (*256*) Changes in phenology of Daphnia across lakes in the northern hemisphere (*187*) Climate change impacts phenology and seasonal dynamics of phytoplankton in lakes (*257*)	flowers and delayed pollination (*155*) Invasive species outperform native species in their flowering response to climate change (*258*) Expanded reproduction of crop pests due to warming (*259*) Altered growing season of maize and wheat globally led to decline of 3.8% and 5.5% yield, respectively (*146*) Increases in a disease vector survival has led to worsened medical conditions (*260*) Warmer autumns and winters allow herbivores to delay diapause resulting in high damage to economically important trees (*261*) Lyme disease-carrying blacklegged tick, *Ixodes scapularis*, exhibited an overall advancement in nymphs and larvae phenology since 1994 (*171*)
Population dynamics: **Recruitment** **Age structure** **Sex ratio** **Abundance**	Meta-analyses- (*37*) Declines in canopy-forming macroalgae (*262*, *263*) Shifts in composition and structure of	Meta-analyses- (*10*, *195*) Decreases in population, changes in age structure and reduced recruitment	Meta-analyses- (*141*, *270*) Decrease of cold-stenothermal species such as coregonids and salmonids and an increase in eurythermal	Reduced growth in fisheries (*217*) decline in fisheries (*275*) Failed recruitment in important freshwater fish, yellow perch (Perca flavescens)

	copepod communities (*264*) Declines in sea ice associated bird and mammal species (*74*, *265*) Lower number of old corals (*266*) Altered sex ratios (*31*)	(*267*) Increases population size in southern ranged species and declines in population in northern ranged species in USA (*268*) Thermophilization of temperate systems causes decline in cold-adapted species and increased abundance in warm-adapted species (*101*, *269*) Population increases (*268*) In Europe, warm-adapted bird species increased in abundance on average since the 1980s and cold-adapted species having declined in abundance over the same period (*80*) Decrease in juvenile survival of Alpine marmot from constraints on life history traits (*56*)	species, and changes in age structure (*142*) Failed annual recruitment in cold-water fish due to shortened, warmer winters (*233*) Impact of heat waves on the dynamics of zooplankton depends on spring temperatures (*271*) Increased abundance of golden-brown algae (*79*) Cause of the recent success of small planktonic diatoms in many relatively oligotrophic lakes (*254*) Temperature linked changes in abundance of noble crayfish (*272*) Climate change correlated with long-term decline in a stream salamander due to increased flood events and reduced survival during metamorphosis (*273*) Decreased winter severity ehanced viability of a montane frog population by increasing survival and breeeding probabilty (*274*)	(*233*) Decreases and increases in important fishery species (*142*) Loss of Antarctic Krill, and commercially important marine crustacean (*275*) Changes in populations of disease vectors for humans (e.g., mosquitos; (*276*)) and in fisheries (*277*), leading to altered disease risk for humans (*167*) Changes in Arctic ice breakup has increased risks for fishing and hunting (*278*) Decline in apex predators and economically important species for tourism (*81*, *279*) Altered tree recruitment responses in hardwood forests (*280*) Changes in fisheries tracks changes in seas surface temperature (*281*) Increased herbivory on commercially important trees (*282*)
Distribution: **Habitat quantity and quality/Ecological niche**	Meta-analyses- (*37*, *71*, *235*, *283*, *284*) Global marine range shifts (*37*)	Meta-analyses- (*10*, *96*, *283*, *284*, *290*, *291*) Latitude and altitude range shifts (*10*, *93*, *94*,	Meta-analyses- (*10*, *57*, *295*) Reduction in thermal habitat for stream salmonids (*76*)	Contribution to the decline of pollinators (*300*), decline in important freshwater fisheries (*77*), increased costs associated with

Range size **Range localization**	Retreat of temperate kelp forests (*262*) Latitudinal shifts and deepening of fish assemblages (*285*, *286*) Deepening of marine fishes distributions (*91*, *287*) Northern range shifts in corals (*86*) Overall range contraction in cold-adapted copepods species and range expansion in warm-adapted species (*288*) Poleward expansion of coastal mangrove forest (*289*)	*96*, *207*, *292*) Range contraction and expansion (*84*, *92*, *158*) Changes in range localization (*158*) Increased range disjunction (*97*) Range shift associated with host use shift in the brown argus butterfly (*293*) Increases in the latitude of distribution centre and northern limits of lizards in China (*294*)	Latitudinal range shifts in lake baitfish and sportfish (*88*) and range shifts in stream fish (*89*, *295*, *296*) Expanded the the spatial extent and duration of preferred thermal habitat for three Lake Superior fishes, and reduced it in another (*297*) Distribution shifts in bi-phasic dragonflies throughout Europe (*51*, *296*) Ranges of cold-water fishes has been reduced or shifted to higher altitude or latitude, but most warm-water species have expanded (*295*) A rare Rocky Mountain stonefly has vanished from previously-occupied streams, and colonized new locations at higher elevations (*298*) Scaled-chrysophyte (algal) assemblages increased dramatically in lakes of eastern Canada during the latter part of the twentieth century (*79*) Climate change has facilitated the spread of the invasive tropical cyanobacterium *Cylindrospermopsis raciborskii* (*299*)	fishing (*301*) and decrease in forest productivity (*118*) Spread of allergies and disease from novel vectors (*167*, *170*, *260*) Changes in the distribution of ‘game’/recreational fish species (*88*, *296*) Increase and spread of the toxic cyanobacterium *Cylindrospermopsis raciborskii* in temperate freshwater systems (*299*) Shifts of distribution and declines in endemic ice-associated marine mammal species impacts people living in the Arctic within subsistence hunting cultures (*74*)
Interspecific relationships: **Loss of synchronization** **Uncoupling (symbiosis, mutualisms, etc)**	Match/mismatch of time of spawning of marine bivalve with that of the phytoplankton bloom and the settlement of juvenile shrimps on the marine tidal flats (*302*)	Meta-analyses- (*101*, *108*) Phenological mismatches have been observed between butterflies and their annual host plants, with the plants dying before	Meta-analyses- (*108*, *270*) Uncoupling of trophic linkages between phytoplankton and zooplankton (*60*) Paleo-ecological evidence of shift from	Loss of food sources resulted in population decline in lake charr, a commercially important fish species (*116*) Emerging Vibrio infection risk to people due to increased seas

New interactions (predation, competition, etc) **Community composition** **Disease spread**	Coral bleaching (*73*) Tropicalization of temperate systems creates new interactions between fish communities (*90*) Borealization of fish communities in the Arctic (*91*) Increased disease incidence in corals, shellfish, and other taxa (*82*, *277*) Shift in coral community composition to stress-tolerant taxa (*303*) Climate-driven regime shifts across tropical, temperate and Arctic marine ecosystems (*112*, *130*, *304*)	the insect larvae were ready to enter diapause (*113*) Increased herbivory (*282*) and climate linked disease (*81*, *279*) Community turnover-replacement in birds (*109*) Turnover in butterfly communities (*110*) Similarly, short-distance (but not long-distance) migratory hosts of the brood-parasitic Common Cuckoo *Cuculus canorus* have advanced their arrival dates more than the cuckoo, and this mismatch may be contributing to the decline of cuckoo populations in some countries (*305*) Thermophilization of plant communities triggers turnover and new interactions (*101*, *269*) Interspecific competition (*105*) Shifts in community composition of European butterflies and birds (*306*) Woody plants are invading arctic and alpine herb-dominated communities (*92*) Increased incidence of avian malaria (*225*) Bee pollination disruption in an orchid (*307*)	generalist to the occurrence of more specialized cladoceran taxa in Canadian Arctic lakes following warming (*115*) Disrupted trophic dynamics in lakes (*142*) Climate driven regime shift in algae and invertebrates in lakes (*308*) Impacted life-cycle through loss of food sources (*116*) Changes in community composition in lake fish (*232*) Paleo-ecological analyses indicate that recent climate change has impacted diatom community composition in lakes across climatic zones (*254*)	surface temperatures (*168*, *169*)
Productivity: **Biomass** **Primary productivity**	Large scale changes in phytoplankton biomass (*119*, *120*) Increase in net primary production (*309*)	Changes in global net primary productivity (*125*)Overall reduction in above-ground biomass in the Amazon due to increasing climate variability (*129*)	Reduction in primary productivity (*122*) Reduced phytoplankton growth (*123*) and associated decreases in fish yields (*122*)	Reduced primary productivity results in decreased fish yields (*122*) Harmful cyanobacteria

			Repeatable signal of increased cyanobacteria biomass with higher winter and spring temperatures across lakes in Europe (*188*) Cyanobacteria blooms impacted by heat waves and thermal stratification linked to climate change (*310*, *311*) Changes in production and abundance of different zooplankton species in Alaskan lake (*312*) Increase in pelagic relative to benthic algal production in alpine lakes (*313*)	blooms (*188*, *311*)



EVIDENCE OF IMPACTS

GENETICS	M	F	T
Changes in genetic diversity	X	DD	X
Genetic adaptation to abiotic changes	X	X	X
Genetic adaptation to biotic changes	DD	DD	DD
Hybridization and hybrid zones	X	X	X
Landscape genetic patterns	DD	DD	X

MORPHOLOGY			
Changes in body size and shape	X*	X*	X
Color	DD	DD	X

POPULATION DYNAMICS			
Recruitment	DD	X	X
Age structure	X	X*	X
Sex ratio	X	DD	DD
Abundance	X*	X*	X*

DISTRIBUTION			
Habitat quantity & quality	X	X	X
Range size	X*	X*	X*
Range localization	X*	X*	X*

PRODUCTIVITY			
Biomass	X	X	X
Primary Productivity	X	X	X

PHYSIOLOGY	M	F	T
Impact on activity rates	DD	X	DD
Sex determination	X	DD	X
Disease susceptibility	X	DD	X
Life history traits	X*	X	X
Survival	X	X	X

PHENOLOGY			
Migration	X*	X*	X*
Budding and flowering	NA	NA	X*
Growing season length	X	X	X*
Life cycle processes	X*	X*	X*
Hibernation and diapause	DD	X	X
Asynchrony	X*	X*	X*

INTERSPECIFIC RELATIONSHIPS & DISEASE SPREAD			
Loss of synchronization	X	X	X
Uncoupling	X	X	X
New interactions	X	X*	X*
Species composition	X	X*	X*
Disease spread	X	DD	X

LEVELS OF BIOLOGICAL ORGANIZATION
(ORGANISM, SPECIES, POPULATION, COMMUNITY)
M=MARINE, F=FRESHWATER, T=TERRESTRIAL
X = EVIDENCE OF OBSERVED IMPACT
DD = DATA DEFICIENT, NA = NOT APPLICABLE
* IMPACT TO PROCESS ASSESSED IN META-ANALYSIS PER ECOSYSTEM

Figure S1 Evidence of observed climate change impacts on ecological processes across the Earth's marine, terrestrial and freshwater systems.
The presence of case studies showing impacts on the different levels of biological organization and its inner components across the Earth's marine, terrestrial and freshwater ecosystems (see Table S1 for a complete list of processes). The * indicates whether the impacted process was assessed in a meta-analysis (in addition to case studies). Thus, two stars (**) indicate that two processes were assessed in at least one meta-analysis. (image credit: Stacey Jones/ Michele Wood/IFAS)

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