Compendium of Scientific and Practical Findings Supporting Eco-Restoration to Address Global Warming

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About Biodiversity for a Livable Climate

Biodiversity for a Livable Climate, bio4climate.org, is a 501(c)(3) non-profit founded in 2013 whose mission is to support the restoration of ecosystems to reverse global warming. We are:

- ***A think tank***, creating research and reports (such as this Compendium), and presenting conferences on the science and practice of eco-restoration with speakers from around the world.

● ***An educational organization***, offering presentations, courses and materials, including over 200 videos of speakers (with over 230,000 views on YouTube) from our 13 conferences since November 2014 (bio4climate.org/conferences), with many restoration and climate-positive examples from both scientists and practitioners.
● ***An advocate*** that reaches out to other organizations to encourage and facilitate the incorporation of eco-restoration as a climate solution into their own messaging and actions. We seek to connect to other groups and projects to help nourish and advance their own growth, and carry messages among groups to collaboratively learn and build on each other's efforts, and occasionally facilitate the emergence of new groups. Since climate affects everyone, every organization has to deal with it in its own way, and we strive to help with the transition.
● ***An activist group*** that engages in non-partisan political processes. For example, we helped shepherd a bill through the legislative process in 2017 to establish a Maryland Healthy Soils Program.
● ***A partner*** with John D. Liu's Ecosystem Restoration Camps movement (https://ecosystemrestorationcamps.org) in helping to apply eco-restoration knowledge and expertise towards the recovery of lands around the world.

We are a small 501(c)(3) non-profit with a major impact in addressing climate, and we rely on your generous contributions! Please go to www.Bio4Climate.org/Donate to join our monthly donor program, or to make a one-time donation, all tax deductible. Many thanks!

Suggested Citation

Compendium of Scientific and Practical Findings Supporting Eco-Restoration to Address Global Warming, Vol 5 No 2, January 2022, https://bio4climate.org/resources/compendium/. This is a collection of article summaries and commentary that will grow as new literature becomes available and as older literature is re-discovered.

Acknowledgements

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Conversion table

hectares vs. acres	1 ha ≈ 2.5 ac
megagrams vs. tons	1 Mg = 1 metric ton
teragrams vs. tons	1 Tg = 1 million metric tons
petagrams vs. gigatons	1 Pg = 1 billion metric tons (1 Gt)
weight[1] carbon vs. weight CO_2	12/44
parts per million CO_2 vs. weight of carbon[2]	1 ppm CO_2 ≈ 2 Gt carbon

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[1] We refer to carbon in soils and biomass, etc. by weight of carbon; atmospheric carbon may be referred to by weight of carbon *or* by weight of CO_2, a frequent source of confusion.

[2] ppm is a volume measurement; 1 ppm in the total volume of earth's atmosphere is approximately equal to 2 gigatons of carbon by weight – and yes, this can be confusing too. Moving 1 ppm CO2 from the atmosphere results in 2 Gt carbon added to soils or other carbon sinks.

Relationships between vegetation and temperature

Earth is heating up: “Global surface temperature was 1.09°C higher in 2011– 2020 than 1850–1900,” according to the Intergovernmental Panel on Climate Change (IPCC)’s 6th Assessment Report.[3] Yet the mercury is not rising uniformly around the world – the Arctic is warming faster than are the lower latitudes, and temperatures over land are higher than over the ocean. Local temperatures everywhere are also affected by the type of land cover, with paved areas being hotter than vegetated land.

In Phoenix, Arizona, the temperature topped 110°F during the summer of 2020 – not just once, but for 53 days.[4] In the same year, Los Angeles experienced its hottest day ever: 122°F. Paris’ hottest day record was broken in 2019, and Buenos Aires’ second and third hottest days ever were in January 2022 (its hottest was in 1957). While climate change is to blame for the world’s increasing frequency of heatwaves, cities additionally experience the “urban heat island” (UHI) effect, which can add as much as 20°F compared to their rural surroundings.[5]

To deal with heatwaves, the city of Phoenix established a new team to manage the public health effects of heat and find ways to reduce it. Part of the plan is doubling the city tree canopy to 25% coverage. Urban heat islands are created by a low ratio of vegetated surfaces relative to concrete, asphalt, and other unvegetated and impervious surfaces, which absorb sunlight as heat and radiate it back out. By contrast, plants use the sun’s energy to transpire water into the atmosphere, a process that cools rather than heats the surrounding air.

Many cities are planting trees to dampen scorching summer heat as public awareness of the relationship between vegetation and the UHI grows. Expanding public green space and tree canopy is a practical way for localities to adapt to the juggernaut of a changing climate because increased vegetation cover not only lowers local temperatures, but can also reduce the severity of flooding and drought by improving rainwater infiltration.

Just as increasing tree cover reduces temperatures in cities, reforestation has a cooling effect at regional and even global scales. The studies profiled below explore a variety of aspects of the relationship between vegetation types, especially forests, and

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[3] https://www.ipcc.ch/report/ar6/wg1/
[4] https://www.theguardian.com/us-news/2022/jan/27/phoenix-arizona-hottest-city-cooling-technologies
[5] https://nihhis.cpo.noaa.gov/Urban-Heat-Islands/Understand-Urban-Heat-Islands

temperature. All produced in the past ten years, these studies show that reforestation (establishing forest on previously forested land) and afforestation (foresting land that was not previously in forest) can lower temperatures, and that deforestation, conversely, has raised temperatures across vast areas.

For example, historical conversion of natural forests in the midlatitudes to cropland and pasture has more than tripled the occurrence of hot-dry summers in those areas [Findell 2017]. Clearing forests heats the land not only by releasing CO_2, which contributes to the greenhouse effect, but also changes the albedo (reflectivity), surface roughness, and evapotranspiration (ET) rates of land surfaces. Land-cover changes affect the temperature through biophysical exchanges of water and energy between the land and the atmosphere.

By 1920, the biophysical effects of deforestation were the main cause of increasing temperatures in deforested parts of North America and Eurasia [LeJeune 2018]. Over the 20th Century, greenhouse gases started to play a bigger role in regional heating. Today, the combined effects of the biophysical changes and greenhouse gas emissions wrought by deforestation account for an estimated half of the temperature rise since pre-industrial times in deforested areas of the midlatitudes [LeJeune 2018].

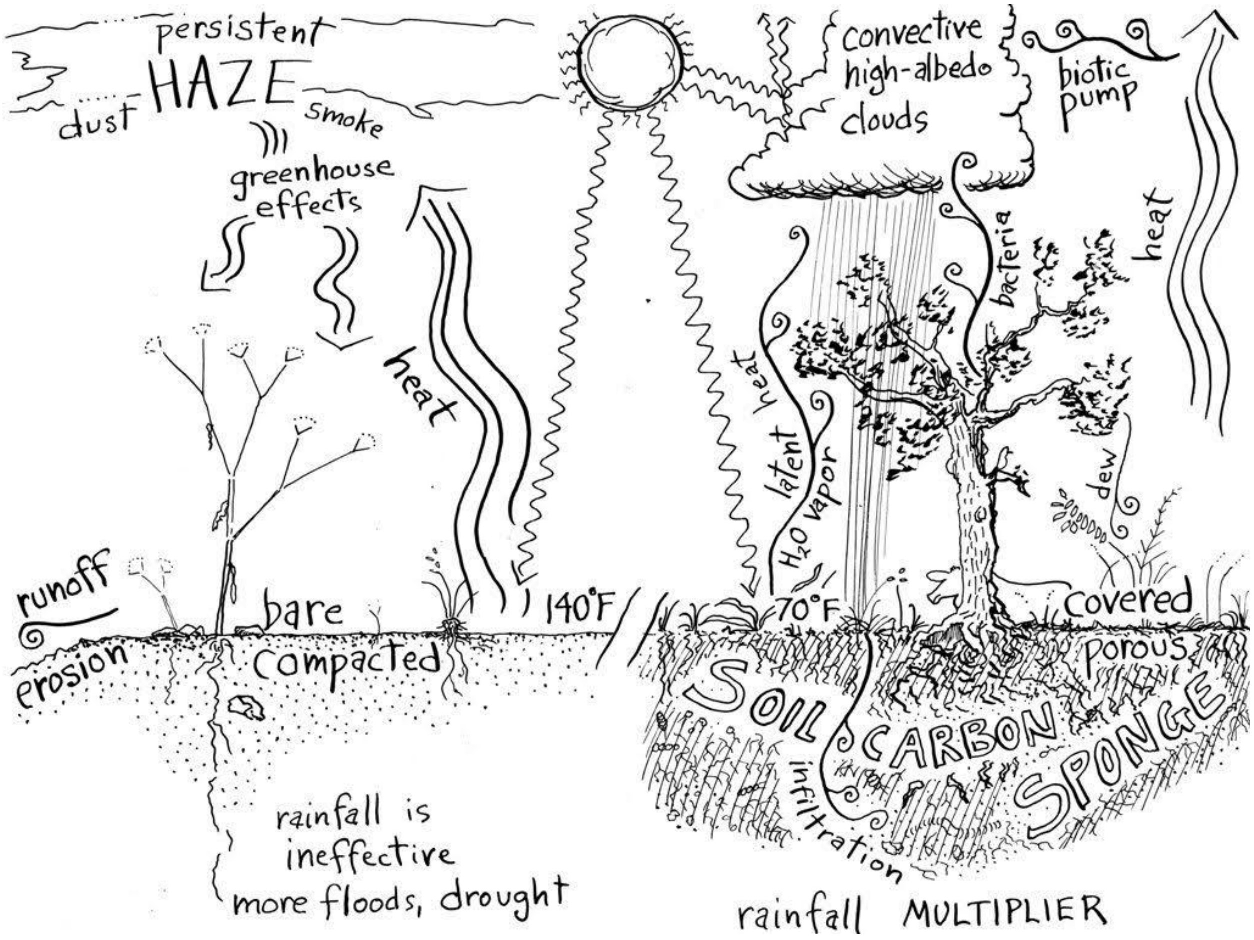
Interestingly, the presence of forests affects surface temperatures differently depending on latitude, although globally, vegetation gain has a net cooling effect [Piao 2020]. In boreal regions, forestation is associated with a warming effect due to a lower albedo of forests compared to non-forest land. By contrast, *de*forestation warms the mid-latitudes and tropics - in spite of the lower surface albedo of forested land. The cooling effect of ET drives temperature regulation in the tropics, while both ET and cloud formation from forests cool the mid-latitudes.

The Jambi province of tropical Sumatra, Indonesia, warmed an average of 1.05°C between 2000 and 2015, a period that coincided with rapid deforestation [Sabajo 2017]. The forests that remained in Jambi during this period also warmed slightly, but much less so than the region as a whole. The authors suggest that the smaller temperature rise inside forests reflects global warming, while the greater regional warming is due to the combined effect of global warming and the biophysical effects of local deforestation.

Vegetation cover both affects and is affected by climate change. Piao et al. [2019] documented an increase in global greening since 1980, which they attribute in part to growth-inducing impacts of climate change. Warmer temperatures and the fertilization effects of higher CO_2 concentration, but also nitrogen deposition and direct afforestation efforts, all have increased vegetation cover, though not evenly across the planet, and not necessarily where it would have the greatest cooling effect. For example, warmer temperatures increase vegetation in the northern latitudes by lengthening the growing season, but reduce vegetation in the tropics where historical temperatures are already optimal for plant growth.

In addition to modulating temperatures, forests also influence precipitation. Through ET – the very same mechanism responsible for cooling the land – forests recycle water back into the atmosphere. Globally, at least 40% of the rain that falls on land comes from evapotranspiration on land, while as much as 70% of rain originating over the Amazon is ET-fed [Ellison 2017]. In Europe, converting a limited proportion (not expected to impinge on food security) of agricultural lands would increase rainfall on the continent by an estimated 7.6%, an important augmentation given the growing frequency of drought there [Baker 2021].

The role that forests and other natural vegetation types play in mitigating global warming and softening the blow of climate extremes has not always been universally clear, but this is changing. The studies highlighted below, which illustrate the heat- and drought-limiting capacity of forests, are among a growing body of work pointing to the importance–and power–of natural climate solutions.



Credit: Peter Donavan (soilcarboncoalition.org)

Summaries of articles showing the cooling effect of vegetation

Cloud cooling effects of afforestation and reforestation at midlatitudes, Cerasoli, Jin & Porporato 2021

Reforestation and afforestation (R&A) are well-established climate mitigation strategies in the wet tropics due to high carbon sequestration rates of forests/trees. However, at high latitudes (boreal regions), the low albedo of trees–compared to snow and other lighter land surfaces–leads to the absorption of energy, thus creating a warming effect that has a greater impact on temperature than the carbon capture accomplished by the limited vegetation productivity in boreal regions. This study explores the balance between albedo and carbon sequestration of forests at mid-latitudes, which has been less clear.

The authors found that forested areas have greater cloud cover than other types of land cover at midlatitudes, resulting in a higher albedo at the top of the atmosphere–where the clouds are–and leading to greater cooling. Specifically, they found “an association of forested lands with increased cloudiness… As a result, forests reflect extra solar radiation and thus reduce the radiative impacts of the lower surface albedo. This in turn implies a cooling effect of R&A at midlatitudes” [Cerasoli 2021: 1-2]. The increase in cloudiness is due to earlier afternoon cloud formation over forests compared to other vegetation types in wet regions.

> Our results provide substantial evidence of remarkable benefits of R&A [reforestation and afforestation] around the 30° to 45° latitudinal range, due to the combined benefits of biomass gain and promotion of cloud formation over forests [Cerasoli 2021: 4].

The duality of reforestation impacts on surface and air temperature, Novick & Katul 2020

While reforestation has been widely heralded as a means of sequestering carbon into the soil, there is growing evidence that it also serves to directly cool the land surface. But forests’ impacts on air temperature (measured over forests rather than within them) have been difficult to assess because of the confounding impacts of forest canopies on wind and temperature profiles near the surface. This study was implemented to create a new method for assessing to what degree forests also cool the air.

Most studies measure surface temperature, which “represents the aggregated temperature of solid canopy and soil elements,” and is measured at a midway point between the ground and the top of the canopy. Air temperature, on the other hand, is measured above the vegetation canopy (whether grasslands or forest). The study site, located in the Piedmont region near Durham North Carolina, consists of an old-field grassland, a pine forest, and an unevenly aged oak hickory forest, all within close proximity to each other. The study assessed temperatures at various heights in and above the grasslands and the two forests.

The authors found that surface temperatures are much lower in forests than in grassland; this difference often exceeds 5°C at midday during the growing season. Furthermore, the air is cooler over forests than over grasslands, though to a lesser degree than the surface temperature difference. The annual average air temperature difference of forests compared to grassland is 0.5°C to 1°C, while the difference reaches 2°C to 3°C during daytime growing season periods.

“Making the connection between land cover, surface temperature, and air temperature is becoming necessary for obtaining a complete picture of the climate mitigation and adaptation potential of managed land cover changes, including reforestation,” the authors conclude. “This energy balance perspective on the climate mitigation and adaptation potential of reforestation is especially relevant right now” given a recent global surge of interest in reforestation to sequester carbon [Novik & Katul 2020: 13].

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Characteristics, drivers and feedbacks of global greening, Piao et al. 2019

The amount of Earth’s green cover (measured as Leaf Area Index[6]) has increased globally since 1980, especially in northern latitudes, where growing seasons have lengthened. This is due mainly to increasing CO_2 concentration, but also to warmer temperatures and changing precipitation patterns, nitrogen deposition, and land-use change (such as afforestation in China). Higher ambient CO_2 can stimulate photosynthesis and reduce water loss, but the extent of the CO_2 fertilization depends on the availability of other key nutrients (nitrogen and phosphorus) and water. Warmer temperatures due to climate change have increased greening in northern latitudes by extending the growing season, but diminished greening in the tropics, where temperatures were already optimal.

Greater global green cover has observable feedbacks on climate and the carbon cycle. In addition to offsetting 28% of anthropogenic emissions since 1980, vegetation affects hydrological cycles and air-surface temperatures. Since the 1980s, increased global evapotranspiration (ET) is mainly attributable to increased global greening. Higher

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[6] Leaf Area Index (LAI) is the quantity of leaf area per unit ground surface area; it’s a way to quantify the thickness of a vegetation canopy.

transpiration rates from vegetation can reduce or enhance groundwater storage locally, depending on how the atmospheric moisture generated through evapotranspiration is recycled into rain and where that rain falls. In the world's great rainforests, vegetation preserves groundwater.

> The enhanced precipitation over transpiring regions is particularly evident in moist forests like the Amazon or Congo, which are 'closed' atmospheric systems where 80% of the rainfall originates from upwind ET. Such an efficient atmospheric water recycling mitigates water loss from the soil, sustains inland vegetation and maintains mesic[7] and humid ecosystems [Piao 2019: 9].

Vegetation affects land-surface temperature by way of ET (cooling effect) and albedo (warming or cooling effect, depending on how dark or light the surface is). While the relative strength of ET versus albedo varies by latitude, the net global effect of increasing vegetation cover is one of cooling the land surface.

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Historical deforestation locally increased the intensity of hot days in northern mid-latitudes, Lejeune 2018

Deforestation has contributed to warming in the northern mid-latitudes of North America and Eurasia not only through a large contribution to global CO_2 emissions, but also through biogeophysical effects. The latter refers to land-surface effects such as albedo and evapotranspiration, which vary according to the type of land cover. This study uses models to demonstrate that deforestation in the northern mid-latitudes has increased the intensity of hot days by about a third since pre-industrial times. Factoring in deforestation's contribution to greenhouse gas emissions further increases deforestation's heating effect.

> Our best estimate suggests that the present-day contribution of deforestation to the TX_x [yearly maximum temperature, or "hot days"] increase over this region still equals at least 50% once the warming entailed by the LCC [land cover change]-induced carbon emissions is considered [LeJeune 2018: 4].

"Extensive deforestation took place early in the industrial period over the northern mid-latitudes," and then slowed down in the 20th Century [LeJeune 2018: 4]. By 1920,

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[7] Mesic refers to moderate moisture levels.

modeled increases of temperature “through biogeophysical effects had already reached 0.3°C (~75% of their present-day values) over the most deforested areas of North America and Eurasia. On average before 1920, local deforestation was responsible for most of the TX_x [yearly maximum temperature] warming over these regions” [LeJeune 2018: 4]. Warming caused by greenhouse gases became more important during the 20th Century, “leading to a total warming of 1.3°C over North America and 1°C over Eurasia by the present-day” [LeJeune 2018: 4].

Expansion of oil palm and other cash crops causes an increase of the land surface temperature in the Jambi province in Indonesia, Sabajo 2017

Turning lemons into lemonade, Sabajo et al. have used the great expansion of oil palm plantations and other crops in Indonesia to examine how such land-use change affects land surface temperature (LST). The authors observed a warming trend in the Jambi province of Sumatra of 1.05℃ and 1.56℃ in the morning and afternoon, respectively, between 2000 and 2015. The average morning (10:30 am) temperature increased by 0.07℃ per year; the midday afternoon (1:30 pm) temperature increased by 0.13℃ per year.

During roughly the same period (2000-2010), forest area decreased in Jambi by 17%, while oil palm and rubber plantations greatly expanded. Given that LST *within* the province’s remaining forests increased only .04C per year at 10:30 am, which the authors attribute mainly to global warming, they concluded that the overall higher province-wide daytime temperature increase was caused by the observed land cover change.

The team also compared temperatures between different land uses: forest, oil palm and rubber plantations, urban areas, and bare land. Despite having a higher albedo (reflectivity) than the forest areas, all converted (non-forest) lands were nonetheless warmer than forests, “suggesting that the albedo was not the dominant variable explaining the LST” [Sabajo 2017: 4629]. Evapotranspiration (ET) played a greater role. Non-vegetated surfaces (urban and bare) were the warmest.

The authors conclude: “The warming effect after forest conversion results from the reduced evaporative cooling, which was identified as the main determinant of regulating the surface temperature” [Sabajo 2017: 4631].

The impact of anthropogenic land use and land cover change on regional climate extremes, Findell et al. 2017

This paper analyzes how land use and land cover change (LULCC) affects temperature and humidity. The authors examined the differential effects of forest versus deforested land on temperature and humidity by comparing different land-cover models. One model simulated the total potential vegetation (“PotVeg”) that would cover Earth in the absence of human interference, while the other was based on historical data of land use changes that occurred over a recent five-decade period (“AllHist”).

They found that deforested lands in mid-latitudes (North America, Eurasia) in the AllHist model are warmer and drier compared to the same lands covered in forest in the PotVeg model. Specifically, “conversion of mid-latitude natural forests to cropland and pastures is accompanied by an increase in the occurrence of hot-dry summers from once-in-a-decade to every 2–3 years” [Findell 2017: 1]. “Based on these simulations, the conversion of forests to cropland is coincident with much of the upper central US and central Europe experiencing extreme hot, dry summers” [Findell 2017: 6].

Local temperature response to land cover and management change driven by non-radiative processes, Bright et al. 2017

Local temperatures are affected not only by global climatic factors, but also by radiative (albedo) and non-radiative (evapotranspiration and convection) mechanisms related to local vegetation cover. Through evapotranspiration, solar energy is converted to latent heat and released from the planet’s surface, while convection refers to the turbulent mixing of air that dissipates sensible heat. The authors state that while albedo (reflectivity of land surface, which is often lower on forested land) is increasingly accounted for alongside greenhouse gases in climate models, the non-radiative mechanisms are not. However, the evapotranspiration and convection facilitated by vegetation have an important cooling effect and should therefore be included in models to avoid the risk of “promoting land sector policies that may be counter to the aims of mitigation or adaptation” [Bright 2017: 296].

The authors demonstrate that “non-radiative mechanisms dominate the local response in most regions for eight of nine common LCMC perturbations” [Bright 2017: 296]. Land cover and land management changes (LCMC) considered in the study include converting cropland or grassland to deciduous or evergreen forests. The authors found that gains in forest cover increased annual cooling in all but the northernmost latitudes, where the lower albedo of forests compared to grasslands had a warming effect that was stronger than the cooling effect of non-radiative mechanisms. In many regions, including much of Europe, the US, and the tropics, non-radiative cooling dominated albedo effects. “Over annual timescales, forest cover gains result in net cooling for many of the densely populated regions of the planet” [Bright 2017: 298].

Bright et al. conclude that “benchmarking the locally driven LCMC effect to that driven by global forcers (such as CO_2) can provide an additional perspective by which to support the valuation of vegetated ecosystems and the local climate regulation services that they provide” [Bright 2017: 301].

Trees, forests and water: Cool insights for a hot world, Ellison et al. 2017

This article (also highlighted in Compendium v2n1) reviews research on the benefits of tree cover in relation to water and energy cycles.

Forests help produce rain. Vegetation releases water vapor through transpiration, increasing atmospheric moisture that is then transported by wind. In fact, “over most of the tropics, air that passes over forests for ten days typically produces at least twice as much rain as air that passes over sparse vegetation” [Ellison 2017: 53]. Forests also release biological particles, such as spores, bacteria and pollen into the atmosphere. Water condenses around these particles, forming raindrops.

In addition to the atmospheric moisture produced by forests that is transported by prevailing winds to generate downwind rain, forests also help transport moisture from the coasts to the interior of continents. According to the biotic pump theory [Makarieva & Gorshkov 2007], evapotranspiration over coastal forests creates low pressure zones that draw in atmospheric moisture from the ocean. This oceanic moisture eventually comes down as rain over land. Deforestation of coastal forests thus reduces this influx of moisture to land, while deforestation anywhere can decrease the reliability of rainfall downwind.

Through shading and evapotranspiration, forests cool the Earth's surface in tropical and temperate climates. Due to a lower albedo compared to other land cover types at high latitudes, boreal forests potentially contribute to local warming. However, forests also increase cloud cover and thus albedo, higher in the atmosphere. In the absence of vegetation, such as in cities, solar energy remains in the environment in the form of heat, rather than driving evapotranspiration.

> Using the sun's energy, individual trees can transpire hundreds of liters of water per day. This represents a cooling power equivalent to 70 kWh for every 100 L of water transpired (enough to power two average household central air-conditioning units per day) [Ellison 2017: 54].

High-elevation forests have a unique potential to intercept fog and cloud droplets, which boosts tree growth, evapotranspiration, groundwater infiltration, and ultimately contributes up to 75% of catchment runoff. Tree cover can improve water infiltration due to increased organic matter to hold water and the presence of tree roots, which loosen and shade the soil and channel water into the ground. In areas where infiltration rates are greater than transpiration rates, the presence of trees increases groundwater recharge.

All of the aforementioned mechanisms distribute water naturally, hence reducing floods.

Ecological roles of animals

Animals contribute vitally to Earth's water, carbon, and nutrient cycles. Every ecosystem is supported by uncountable animal species, ranging from birds to insects and mammals to fish, as well as microscopic organisms. The devastating news is that the Earth is losing about 150 animal, plant and microbial species every day, mostly due to human activities.[8] Understanding the ecological value of animals could bring attention to and support for actions and policy to protect animals and the ecosystems they compose.

On land, large herbivores can enhance carbon storage and maintain a healthy ecosystem. Grazing is commonly viewed as damaging to the grasslands–and that is the case when herds are overpopulated or otherwise not leaving sufficient time for pastures to recover after grazing. But when herbivore populations are in balance with the ecosystem, grazing is beneficial and stimulates the growth of grasses. Grazing animals nourish soil with their waste and churn the soil to facilitate the incorporation of organic

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[8] https://www.cbd.int/doc/speech/2007/sp-2007-05-22-es-en.pdf

material through daily activity. Grazing also removes pyrogenic (combustible) carbon from the land surface and increases grasslands' fire resistance.

Grazing becomes unbalanced when top predators are lost. Animals and plants have coevolved, each species relying on numerous other species both for food and population control. Just as wolves need elk for food, elk need wolves to keep the herd healthy by eliminating weak and sick elk and keeping local carrying capacity from being breached.

Plants need wolves too, as do all species that depend on those plants when, in the absence of predators, herbivore populations grow too large. In one of the most successful rewilding experiments, the reintroduction of wolves in Yellowstone National Park in the mid-1990s effectively stabilized the elk population, eliminating the need for the government to remove elk from the Northern Yellowstone herd due to overgrazing.

Wolf-mediated control of the herbivore population benefited plant communities, rivers, and streams. Beschta and Ripple [2020] explain that prior to wolf reintroduction, elk grazing along stream banks kept willow trees from growing tall and shading the stream. Overgrazing also eroded the bank and deepened the streambed, ultimately reducing the frequency of the natural overbank flow that had previously nourished the floodplain.

By 2017 (compared to the 1990s), however, these authors write, willow heights had nearly quadrupled, while:

> Canopy cover over the stream, essentially absent in 1995, had increased to 43% and 93% along the West Fork and East Fork, respectively. These recent increases in tall willow heights, greater canopy cover, well‐vegetated streambanks, and the recent development of an inset floodplain all pointed towards a riparian/aquatic ecosystem beginning to recover [Beschta & Ripple 2020: 1].

Australia historically hosted an array of megafauna. Now that some species have gone extinct, there is a void left on the continent. Introduced wild donkeys fill that void by grazing, digging wells, and browsing vegetation. These behaviors improve plant and soil health by contributing to the nutrient cycle. Wild donkeys venture into areas where cows do not, meaning that these non-native species have found their place in Australia's increasingly dry landscape.

Australia is not the only place from which large mammal populations have disappeared. Only one-third of 730 terrestrial ecoregions today have *intact* mammal assemblages, meaning that all of the species that were present on the landscape 500 years ago remain today. Noting that large mammals are critical ecosystem engineers, a 2022 study estimates that the reintroduction of 20 priority species (including bear, bison, beaver, cougar, deer, and gazelle, for example) “can trigger restoration of complete assemblages over 54% of the terrestrial realm,” thus improving overall ecosystem function [Vynne 2022: 1].

Creatures come in all shapes and sizes, and even the smallest ones play an ecological role. By building mounds that support denser, taller vegetation than surrounding land, termites create microclimates in hot arid environments that are up to 4°C cooler than elsewhere on the landscape. Cool, shady termite mounds thus become vital refuges for other species.

Ladybugs contribute directly to agricultural systems by keeping pest populations under control. Ladybugs prey on aphids, mealybugs, and other creatures that have an appetite for crops. Rather than investing in artificial pesticides made up of harsh chemicals that damage beneficial plants and harm wildlife, farmers can work with ladybugs to maintain the health of their crops.

We cannot reestablish the Earth’s balance without addressing the body of water that covers over 70% of the planet. One type of marine invertebrate, the sea sponges, support clean oceans by filtering water. Sea sponges also provide a home for other animals living inside or on their surface, and take part in natural underwater construction by helping corals anchor to substrate. Once corals find a secure place to grow, they build colorful reefs, and sea sponges are one reason these underwater cities continue to flourish.

Sperm whales stimulate carbon sequestration in the Southern Ocean. Lavery et al. [2010] demonstrate that South Ocean sperm whales’ iron-rich feces are a critical phytoplankton fertilizer, boosting photosynthesis and drawing in carbon, which ultimately sinks to the deep ocean. In this way, sperm whales are removing 2.4 X 10^5 metric tons of carbon from the atmosphere annually. However, commercial whaling greatly limits this carbon export activity:

> The reduction in sperm whale numbers owing to whaling has resulted in an extra 2 X 10^6 tonnes of carbon remaining in the atmosphere annually. [Lavery 2010: 3]

Overfishing also reduces the ocean's carbon storage potential. Mariani et al. [2010] found that between 1950 and 2014, the removal of tuna, mackerel, shark, and billfish, mainly by industrial fisheries, prevented 21.8 ± 4.4 Mt C (million metric tons of carbon) from being sequestered. Had the fish not been caught, but rather died a natural death, their bodies would have sunk to the bottom of the ocean and remained there. Unlike animal corpses decomposing on land, which release CO_2, the embodied carbon in marine animals remains in the depths of the ocean after death.

Migratory animals – whether in the ocean, on land, or in the sky – interact in ecosystems at a macroscopic level. Bauer & Hoye [2014] showed that migratory animals influence the herbivory, predatory, and reproductive patterns of other species, redistribute nutrients, and disperse propagules (such as seeds, suckers, or spores), toxicants and parasites along their migration routes. Migrating animals may even enhance (re)colonization of unoccupied or lost habitat through propagule dispersal.

Recognizing and appreciating the importance of other species allows us to reconnect with nature and natural cycles. The mutually beneficial relationships between lands, waterways, and animals render animals inseparable from and indispensable to these ecosystems. Removing just one species from an ecosystem can lead to drastic effects on the entire ecosystem. When species are able fulfill their respective roles in ecosystems, those ecosystems maintain their function and balance.

To learn more about the fascinating and varied ways that wildly diverse creatures help to make our world tick, explore Biodiversity for a Livable Climate's Featured Creature series at https://bio4climate.org/featured-creature/.

Summaries of articles on the ecological roles of animals

Can large herbivores enhance ecosystem carbon persistence? Kristensen et al. 2021

This article considers the overlooked role of grasslands and large herbivores in carbon storage. The principal question the authors pose is: what is the impact of large wild and domestic herbivores on the ability of ecosystems to absorb and store carbon over the long term? Their answer is that the activity of species like cattle, bison, boars, elephants, and rhinoceros, can significantly enhance ecosystem retention of carbon.

Questioning the assumption that fast-growing aboveground vegetation, especially trees, is the primary nature-based terrestrial sink for carbon, the authors argue for a whole-ecosystem carbon storage perspective. One problem with focusing on carbon storage in aboveground vegetation rather than that in the soil, they note, is that vegetation is more transient and vulnerable to disturbances, such as fire, while soil carbon tends to be stable, at least under natural and well-managed grasslands. Furthermore, the authors argue that the conventional focus on aboveground carbon storage has led to the "simplistic" generalization that large herbivores can be expected to damage vegetative ecosystems, and therefore have a negative impact on ecosystem carbon storage.

Yet this view misses the overall ecological impact of large herbivores, such as contributing to the soil through their wastes, and their *bioturbation* (churning of the soil by animals) activity*.* On the surface, large animals trample, forage, wallow and dig; just below the surface, the burrowing and digging of tunnels by soil-dwelling mammals like gophers, moles, voles, and shrews further loosens the soil; still deeper, there is the casting, burrowing and mining by macrofauna like insects, worms and dung beetles. Together, the multi-levelled bioturbation of these different species facilitates the vertical mixing of the organic material, putting it into contact with mineral soil particles for longer-term storage. Large grazing herbivores participate in vertical soil mixing (along with the smaller animals at lower levels in the soil), and therefore play an essential role in the long-term buildup of mineral-associated organic matter.

In addition to disturbing and mixing the soil, and enriching it through their body wastes, large herbivores clear pyrogenic (combustible) material on the ground and low shrubbery, thus increasing fire resistance. Their grazing also increases fine root growth and root exudation, which leads to increased microbial biomass. In turn, "microbial residues and plant exudates are effective substrates for persistent soil organic matter formation in the mineral-associated organic matter" [Kristensen 2021: 4].

In their conclusion, the authors emphasize the ecological value of natural grasslands, and the importance of preserving them:

> Understanding the role that large herbivores may play in enhancing ecosystem carbon persistence, by reducing the flammability of aboveground carbon and shifting carbon storage from vulnerable pools towards more persistent soil pools at the biome scale, is crucial to balancing the ecosystem services provided by

> semi-open herbivore-rich systems against potential services from alternative land-uses, such as afforestation [Kristensen 2021: 9].

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25 years after returning to Yellowstone, wolves have helped stabilize the ecosystem, Peterson 2020

Before the 1900s, wolves and other predators, such as bears and mountain lions, helped control the populations of herbivores in Yellowstone. However, the federal government exterminated these predators in a coordinated campaign. After the last wolf pack was killed, the elk numbers started increasing uncountably. The US Park Service subsequently attempted to control the elk population by shooting the animals or moving them out of the park.

> When the park stopped killing elk in 1968, numbers shot up again from about 5,000 to close to 20,000. For the next several decades, elk cycled through population booms and collapses along with climate fluctuations; hard winters left the ground littered with hundreds of the carcasses of elk that had starved to death [Peterson 2020].

Wildlife officials, therefore, reintroduced wolves back to Yellowstone 25 years ago, which brought the elk population under control and ended their extreme population fluctuations due to climate variability. To study how the wolves maintained the balance, the scientists tracked the wolf packs and recorded details of elk kills by the wolves.

They found that the wolves killed cow elk during the years with normal amounts of rain and snow. During the dry years, when there is less vegetation and therefore less elk food, the wolves targeted bulls. The undernourished elk are generally easier to catch, so the wolves target bulls given their larger size. Sparing elk cows allows the elk to reproduce.

The wolves improve elk herd resilience by eliminating the weak and sick animals. Scientists believed the elk herds are now better prepared for climate change impact, such as the frequent droughts.

The result of reintroducing wolves to Yellowstone showed that wolves stabilize the elk population better than humans can. Now wolves may be reintroduced to other states which are home to a large number of elk.

Can large carnivores change streams via a trophic cascade? Beschta & Ripple 2020

After having been wiped out by the 1920s, wolves were reintroduced to Yellowstone National Park in 1995-1996. This study assessed the importance of large carnivores to wild ungulates' behavior and density, with secondary effects on plant communities, rivers and channels, and beaver communities. Focusing on the West and East Forks of Blacktail Deer Creek, the authors summarized the population trends of wolves, elk, and beaver; sampled the heights, recruitment, and browsing intensity of Geyer willow (a common local tall willow); measured dimensions of the channel, and ascertained beaver dam heights.

After the reintroduction of wolves, the Rocky Mountain elk population decreased from 17,000 in 1994 to about 4,000 to 5,000 in recent years. Browsing intensity therefore greatly decreased, leading to taller riparian willow stems, which is an important food web support and physical habitat for both terrestrial and aquatic wildlife species. The willow canopy cover over the water surface has also increased rapidly over the last two decades, which holds a significant role in supporting the aquatic biota:

> Canopy cover can reduce the amount of solar radiation reaching a stream, especially important during summertime periods when solar angles are high, day lengths are long, and flows are normally low, thereby mediating potential increases in water temperature. Furthermore, invertebrates in the canopies of near‐channel willows provide food for fish and seasonal leaf‐fall represents an important carbon base for aquatic invertebrates which, in turn, provide 'reciprocal flows of invertebrate prey' to adjacent terrestrial consumers [Beschta & Ripple 2020: 8].

Another benefit of protecting the riparian vegetation from herbivores is the improvement of streambank stability. During the period of wolf absence, intensive elk herbivory caused streambank erosion and channel incision (river cuts downward into its bed, deepening the active channel and may lead to dissected landscape), resulting in less frequent overbank flow. The channel incision lowered water tables and reduced subsurface moisture in flood plain vegetation during summer.

The return of wolves started the process of riparian vegetation restoration, which in turn supported stream-dependent species such as beavers. The reduction of elk herbivory increased food sources and materials for beavers to construct dams, while also fostering the narrower and shallower channels preferred by beavers. Thus, along with the recovery of vegetation and channels, beavers have returned in 2018, creating active dams to further rehabilitate the ecosystem.

> If beaver populations continue to increase over time, the ecological effects of these ‘ecosystem engineers’ may well have a significant role in restoring riparian vegetation, floodplains, and channel dimensions for at least portions of northern range streams [Beschta & Ripple 2020: 9].

Pollination by bats enhances both quality and yield of a major cash crop in Mexico, Tremlett et al. 2019

“The majority of the world's 350,000 species of flowering plants rely on animal pollinators for reproduction” [Tremlett 2019: 2]. Of the many vertebrates performing this function, including birds, rodents, and reptiles, bats are thought to be the primary pollinators for about 1,000 species of plants across the tropics.

The authors of this study conducted this research in the municipality of Techaluta de Montenegro, Jalisco, Mexico, where they held exclusion experiments (alternately excluding different pollinator species) on *Stenocereus queretaroensis*, a type of cactus with edible fruit, to determine the efficiency of different pollinators. The experimental treatments allowed the authors to distinguish between nocturnal and diurnal (active in the daytime) pollinators, and between invertebrate and vertebrate pollinators.

Pollination carried out by birds and diurnal insects resulted in low seed sets, significantly lighter fruit weights, and lower sucrose concentrations compared to pollination carried out by bats.

This was the first research study to assess the impact of bat pollination on not only the quality of a high socio-economically important crop but also the yield of the crop.

> We found that in the absence of pollination by nectarivorous bats, yield and quality (i.e. fruit weight, as size determines market value) of *S. queretaroensis* decreased significantly by 35% and 46% respectively. Hence, nectarivorous bats contribute substantially to the economic welfare of the rural production region [Tremlett 2019: 6].

However, despite its economic value, the significance of pollination by bats is not valued and appreciated. It is important to recognize the ecosystem services provided by bats, which might be crucial to sustaining rural livelihoods and well-being.

Equids engineer desert water availability, Lundgren et al. 2014

Many large herbivores may have important roles in dryland ecosystems. Equids such as donkeys and horses, as well as elephants, have been reported to dig wells of a maximum depth of two meters, enhancing water availability for a variety of animals and plants. Noting that this subject has received limited research attention, the authors carried out a study for three summers at the Sonoran Desert of North America to survey changes in groundwater-fed streams and “equid well” water, and the associated effects on the ecosystem.

Effect on animals

They found that the equid wells “provided up to 74% of surface water by accessing the water table” at one of the four groundwater-fed streams they studied [Lundgren 2014: 1]. The wells were especially important at the intermittent stream (unsteady stream that occurs at irregular intervals), providing 100% of available surface water when all other water was lost.

The wells reduced the distance between neighboring water features significantly, thus reducing the distance that animals needed to travel to reach water. The water resources created by the equids also prevented some species from resorting to eating extra plant foods simply to extract its water content, as they are observed to do in the absence of available surface water. Using camera traps, the researchers observed 59 vertebrate species (limited to organisms weighing over 100g and excluding equids) at equid wells, 57 of which they recorded drinking. “Daily species richness was 64 and 51% higher on average at equid wells and background waters [other surface water, such as the streams], respectively, than at dry controls” [Lundgren 2014: 1].

Effects on vegetation

The presence of equid wells enhanced the growth of pioneer trees. The survey showed that the seeding density was higher in equid wells, which function as germination nurseries, than in the riverbank zone. Riverbanks were usually covered by herbs, which reduced the density of trees. Equid wells, on the other hand, provide a non-competitive environment for the small-seeded pioneer trees.

The feral donkeys that dug the equid wells are not native to this dryland ecosystem study site, and yet they proved to mitigate the effects of water reduction and high temperature on biodiversity and ecosystem function. Thus, the ecological roles once played by large native mammals that have since become extinct, can in some cases be filled by non-native substitutes (which are typically viewed as threats to conservation).

Microclimates mitigate against hot temperatures in dryland ecosystems: termite mounds as an example, Joseph et al. 2016

This paper presents an analysis of microclimatic temperature effects of termite mounds in Zimbabwe and South Africa that provide important climatic “refuges” for other local organisms. The research compared the vegetation growing on the mounds with that on control plots in the surrounding savannah with respect to temperature differences. They found that more tall woody vegetation grows on termite mounds, compared to surrounding areas, creating shade that cools the mounds.

The authors observed that: “tall trees, being more prevalent on mounds, provide increased leafy, large-volume canopy and subcanopy vegetation, which in turn furnish more shade relative to the savanna matrix” [Joseph 2016: 7]. They found a 2°C temperature difference on the termite mounds compared to the surrounding area when the surrounding temperature was 34°C; the difference rose to 4°C at 40°C. Thus, these mound microhabitats maintained an even greater ambient temperature difference the warmer the ambient environment became.

Data were collected on 44 large termite mounds, each paired with off-mound savannah plots, in October 2015 (which was one of the hottest months on record in these areas) during the dry season. The mounds were more than 2 meters tall or more than 10 meters in diameter, and they were compared with an equivalently sized circular plot in the surrounding habitat. For each termite mound and control plot, the variables measured included: temperature, humidity, number of trees taller than 4 meters, tree canopy size, and amount of shade.

The median mean shade on mounds was 21% compared to 3% on the control plots, while the median maximum shade was 70% on mounds and only 10% on the surrounding plots, while humidity did not differ significantly. Such microclimates are likely to be important refugia for wildlife as droughts, fire events and higher ambient temperatures become more prevalent due to climate change.

Migratory animals couple biodiversity and ecosystem functioning worldwide, Bauer & Hoye 2014

Billions of animals, including insects, mammals, fish, and birds, migrate through the planet every year, which uniquely influences the environment and the ecological communities along migration routes.

> “The frequency of migrations and the immense number of individuals involved often mean that migrant inputs constitute “resource pulses,” defined as occasional, intense, brief episodes of increased resource availability that can profoundly alter demographic rates and abundances of interacting populations” [Bauer & Hoye 2014: 6]

Effect on nutrients, energy, and toxicants:

Migrants transport nutrients, energy, and other substances from one ecosystem to another, creating a net inflow of energy and nutrients into the destination ecosystem. For example, salmon increased the nitrogen and phosphorus in their spawning habitat by 190% and 390% when migrating from the ocean back to their natal lakes and streams. At the same time, migrants may also introduce and accumulate toxicants, such as heavy metals, to receiving communities.

Effect on propagule dispersal:

Migrants play an important role in dispersing propagules, such as seeds, suckers, or spores across the resident communities.

> In light of the importance of dispersal for population structure, adaptive capabilities, and evolutionary trajectories in theoretical studies, such

> long-distance dispersal events may be highly important for the (re)colonization of unoccupied habitats, the recovery of lost populations, maintenance of gene flow, and gene mixing in metapopulations, even if they are relatively rare events [Bauer & Hoye 2014: 2].

Moreover, migrants could also disperse propagules within resident communities. For example, long-nosed bats are responsible for up to 100% of columnar cacti pollination when they migrate to western Mexico. It is important to note that the timing of migration is very important; the migrants can only serve as major pollinators when visiting the communities during peak flowering.

Effect on parasite dispersal:

Migrants may increase parasite dynamics by facilitating the long-distance dispersal of parasites (including zoonotic pathogens like Ebola that also affect humans) to resident species. A few key mechanisms are involved in migration-facilitated parasite dispersal. For example, migrating animals are likely exposed to a greater range of parasites than are resident species. Some migrant animals may have suppressed immune responses due to the high investment of energy into migration, increasing their susceptibility to infection. In addition, while migrating, animals tend to aggregate in larger groups, thus enhancing transmission rates, compared to other times of the year when they are stationary.

However, the role of migrants in transmitting parasites is complicated. Studies of monarch butterflies have shown that they have a shorter flying distance when infected with parasites, andinfected Bewick’s swans delay their departure and travel shorter distances. These findings suggest that migrants may reduce infection risk through infection-induced delays.

Effect of migratory herbivores (plant-eating species):

Migrants may alter the nutrient cycling, productivity, the biomass of edible plants, and ground cover of dead plant material. The grazing intensity of migrant herbivores is decoupled from the timing of plant growth so plants can grow when they are left, which substantially increases the primary productivity compared to an ecosystem with the equivalent number of resident herbivores.

The outcome of the interaction between migrants and residents differs depending on the food resources. During periods of plenty of food residents could share the excess resources with the migrants. However, during the dry season when food is scarcer, synergistic negative effects may be created.

Effects of migratory predators:

Migratory predators can positively influence the communities through prey population control. For example, birds and bats may control the insect population, which reduces damage to crops. Seasonal outmigration may also reduce pressure on prey in the places left behind by migrants, allowing those populations to regrow.

Effects of migratory prey:

Migratory prey could be an important resource for resident predators. Some predators even time their reproduction to coincide with migratory prey to increase their reproductive rate.

Migratory prey may also provide resident prey with a temporal refuge from predation. However, an abundant number of migrants may harm residents by boosting the abundance of resident predators, which then switch to resident prey after the migratory prey departs.

Many ecosystems have evolved to depend upon the activities of both resident and transitory migrating animals, and understanding these relationships is critical to preserving and restoring ecosystem complexity and resiliency.

> Across the globe, migration is an increasingly threatened phenomenon as a consequence of habitat destruction, creation of barriers, over-exploitation, and climate change. The loss of migrants and migratory behavior also entails the loss of their ecosystem services—the manifold transport and trophic effects outlined above. Management strategies must therefore be designed to conserve not only migratory species but also their ecosystem functions. Yet, the conservation of migrants poses exceptional scientific and societal challenges, as events at each stage of the migratory cycle affect behavior and demographic rates and ecological interactions at other stages [Bauer & Hoye 2014: 9].

Let more big fish sink: Fisheries prevent blue carbon sequestration—half in unprofitable areas, Mariani et. al 2010

The ocean sequesters about 22% of global anthropogenic CO_2 emissions. Marine vertebrates contribute to the ocean's carbon sink capacity in various ways, such as by fertilizing coastal vegetated habitats, and (through the work of marine predators) protecting this vegetation from overgrazing. Additionally, fish sequester carbon in the deep sea when they sink to the bottom after their natural death, whereas fishing releases the carbon embodied in fish back into the atmosphere when the catch is processed and consumed. Large fish (tuna, mackerel, shark, and billfish) that die in the ocean particularly contribute to "blue carbon" because these species are more likely to sink than be eaten near the surface. Unlike the CO_2 released by terrestrial animals after death, the embodied carbon in marine corpses remains in the deep ocean.

This study estimates the extent to which fisheries have obstructed blue carbon sequestration. Mariani et al. report that fishing prevented 21.8 ± 4.4 Mt C (million metric tons of carbon) between 1950 and 2014 from being sequestered in the deep ocean. Industrial fisheries (as opposed to smaller, artisanal fisheries) are responsible for 85% of this extraction.

The amount of blue carbon extracted from the ocean through the harvest of large fish increased by almost one order of magnitude in 65 years (from 0.13 Mt C in 1950 to 1.09 Mt C in 2015). Combining CO_2 emissions from fishing fleet transport and that of the fish removal itself amounts to 20.4 $MtCO_2$ emitted in 2014, which is equivalent to the annual emission of 4.5 million cars.

Moreover, the authors found that government subsidies are encouraging overfishing. Almost half of the blue carbon extracted from the world's oceans comes from areas that would be economically unprofitable without subsidies.

> Our findings thus show that government subsidies, through supporting large-scale exploitation of large-bodied fish that are economically unviable, exacerbate the depletion of a natural carbon sink [Mariani 2010: 2].

Limiting and managing all fisheries on the unprofitable areas of the oceans could reduce CO_2 emissions, rebuild fish stocks, and promote carbon sequestration by increasing the populations of large-bodied fish and the eventual deadfall of their carcasses to the depths.

Iron defecation by sperm whales stimulates carbon export in the Southern Ocean, Lavery et. al 2010

Whales have been viewed as a source of CO_2 because they respire tons of CO_2 annually. However, their feces could possibly offset this impact, as they may be a great contributor to carbon export (removal from the atmosphere) to the depths of the ocean. Iron-rich whale feces stimulate the growth of phytoplankton, which leads to more CO_2 drawn into the ocean through photosynthesis.

Lavery et al. conducted this study to find out whether the 12,000 sperm whales in the Southern Ocean are acting as a carbon sink. The authors wondered whether the whales help the ocean absorb more carbon from the atmosphere than the whales themselves release through respiration. They note that these animals consume prey outside of but defecate within the photic zone (the layer nearest to the ocean surface), raising nutrient availability in the layer of ocean where photosynthesis is possible. Whale feces are also in liquid form, which disperses and persists within this area.

Using existing data on whale populations, consumption patterns, and average rates of iron retention compared to what is expelled, the authors estimate that the South Ocean sperm whales contribute 36 tons of iron per year to the photic zone. After accounting for respiration rates, the authors conclude that whales do act as a net carbon sink by removing 2.4×10^5 metric tons of carbon from the atmosphere annually. Even under conservative scenarios (consumption of prey with lower iron concentrations), whales still help sequester more carbon than they respire.

These animals' contribution to nutrient and carbon cycling in the ocean has previously been overlooked. Their feces not only enhance carbon sink in the ocean but also contribute to increasing numbers of prey. However, the reduction of sperm whales by commercial whaling has reduced krill populations and decreased allochthonous (originating externally) iron inputs to the Southern Ocean by 450 tons annually.

> The reduction in sperm whale numbers owing to whaling has resulted in an extra 2×10^6 tonnes of carbon remaining in the atmosphere annually [Lavery 2010: 3].

In addition to sperm whales, there could be more organisms acting as carbon sinks in the ocean:

> We have restricted our analysis to sperm whales; however, any organism that consumes prey outside the photic zone and defecates nutrient-rich waste that persists in the photic zone would stimulate new production and carbon export. Pygmy and dwarf sperm whales (Kogia spp.) and beaked whales (Family Ziphiidae) fulfill these criteria. The proportion of time baleen whales consume prey at depth is currently unknown, but fin whales (Balaenoptera physalus) dive to at least 470 m while feeding. Seals and sealions often consume prey at depth, but whether the[ir] waste is liquid (and buoyant) requires further investigation. [Lavery 2010: 4]

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