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

Volume 4, Number 2, January 2021

Note: *Each item in the Table of Contents is a live link to its location in the Compendium.*

NOTE: Citations in our text are in brackets. The format is [lead-author year: page number (if a specific quote is referenced)].

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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 4 No 2, January 2021, 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.

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We are most appreciative of the support from our sponsors over the past six years. In particular, the 11th Hour Project provided significant funding for our first two years, and the new and important institution that it helped create, the Regenerative Agriculture Foundation, is continuing its strong moral and financial support. We are also pleased to acknowledge generous conference sponsorship from the Organic Consumers Association, Regeneration International, the Virgin Earth Challenge, Bristol Community College, the Tufts Institute of the Environment, Janelia Foundation, Margaret Roswell, the Overbrook Foundation, and Foundation Earth. Additional important support has been kindly provided by the Nutiva Foundation, the Rockefeller Family Fund, the Savory Institute, Irving House, and the Bionutrient Food Association. We also gratefully acknowledge support from several institutions, including Tufts University, Harvard University, Bristol Community College, and the University of the District of Columbia.

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 carbon vs. weight CO_2	12/44
parts per million CO_2 vs. weight of carbon[1]	1 ppm CO_2 ≈ 2 Gt carbon

[1] ppm is a volume measurement; 1 ppm in the total volume of earth's atmosphere is approximately equal to 2 gigatons 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.

Responding to Wildfire

All over the world, from Australia to Europe to North and South America, wildfires have waged destruction on natural landscapes and human settlements alike. The devastation of these disasters is heartbreaking, and the images of catastrophe – walls of flame, scorched wildlife, a world gone red – are unforgettable. There is no more potent image of the climate crisis than the towering infernos and eerie, hellish, smoke-filled skies that we've seen in this past year.

The question is how we best confront the issue, keeping people safe and ecosystems intact as much as possible. Given that the hotter, drier conditions that climate change causes are exacerbating wildfire seasons in both duration and destructiveness, it is urgent that we better understand fire's natural role in ecosystems and the conditions that cause fires to become ultra-destructive. Wildfire is a complicated global problem that requires locally-informed responses adapted to local ecosystems.

"Fuel load" reduction is a major solution, and this may be part of the answer in certain cases. However, to the extent that hauling out vegetation from a fire-prone site further degrades that ecosystem, this practice may only exacerbate the problem in the long run. Fortunately, many alternative and complementary practices to diminish wildfire ferocity are known. This includes, for example, indigenous prescribed burning, promoting ecosystem health to reduce dryness and drought, favoring native species, and enacting land use policies that discourage development in fire-prone areas.

In discussion of fire and its risks, it is important to first note that not all fire is problematic, and the ideal healthy ecosystem would not necessarily be one without any fire. For example, species in fire-evolved landscapes depend on cyclical fires, and burning can also increase landscape heterogeneity and biodiversity.

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Moreover, a world without fire is impossible, and focusing on total fire suppression is misguided. As environmental historian Stephen Pyne warns, "Removing fire from landscapes that have co-evolved or co-existed with it can be as ruinous as putting fire into landscapes that have no history of it" [Pyne 2020]. In fact, we can fight fire with fire by planning controlled burns, part of the strategy of managing the vegetative fuel available to wildfires.

Since grasses, shrubs, and trees become fuel for a fire, much scientific literature on wildfire examines how to reduce this fuel so that when wildfire does occur, it is less destructive and less far-reaching. Invasive plants are a particularly problematic form of fuel, because they haven't necessarily evolved in fire-shaped landscapes. Fires can quickly gain in intensity when consuming them, and invasive grasses alter the cyclical availability of fuel and increase the frequency of fires [Fusco 2020].

In contrast, native plants in fire-prone ecosystems often evolve with fire playing an ecological role in their habitat, leading them to be more resistant and hardy in destructive blazes. Thus there is a clear advantage to favoring native species over invasive ones, especially since native species also perform ecological functions necessary for the health of the ecosystem and its inhabitants.

It is important to understand that more plant life does not necessarily translate to more fire fuel. The quality of landscape and details such as height, density, fuel bed depth and fuel moisture all matter for fire spread [Nader 2007]. Furthermore, not all vegetation is equally vulnerable. This is not just a matter of the differences between species, but also how landscape differs in its spacing, density, and topological features, making some landscapes more vulnerable to fire spread than others.

Often, our problems with fire are also problems of water. How well hydrated a landscape is can make a crucial difference to its vulnerability to wildfire. In fact, the capacity of land to retain water is linked to vegetation, and specifically to biodiverse vegetated areas. A healthy and hydrated tree or patch of forest may withstand fire that drier and more brittle vegetation does not. Healthy trees may even protect properties from fire, as anecdotes attest [Aubrey 2020].

Plant roots, along with the mycorrhiza and microbes that make up a symbiotic web of linked organisms within healthy soil, create a porous soil structure that water infiltrates when it rains; the soil thus acts as a sort of natural sponge. Unlike dehydrated and degraded soil, which do not absorb and retain water effectively, living soil soaks up precipitation; this reduces runoff and erosion during heavy deluges. Water infiltrating healthy soil hydrates organic matter, is retained in topsoil pores, or makes its way to the water table below ground, which can be thought of as a bank for water. When dry seasons or droughts arrive, this bank provides the moisture needed to keep vegetation healthy--and, when rains arrive again, this bank refills.

Plant presence helps build healthy soil, and it also contributes to the small water cycle (the circulation of water evaporating from land and falling in the form of precipitation over the same environment). For example, scientists have found that many plants release microbes which are borne up on evaporated water droplets and catalyze cloud formation and precipitation in the atmosphere, a phenomenon known as bioprecipitation [Morris 2014]. Plants don't just need rain

– they help create it too. Well-hydrated, fire-resistant plants are part of the key to retaining moisture in landscapes and sapping wildfire of its power.

Beavers also contribute to water retention on the landscapes they inhabit. They play a major ecological role by creating and preserving wetlands, so much so that they are sometimes called ecosystem architects or engineers.The hydrating effects of beaver activities have even been found to create areas that resist fire even while neighboring landscapes burn. Some experts suggest that “perhaps instead of relying solely on human engineering and management to create and maintain fire-resistant landscape patches, we could benefit from beavers’ ecosystem engineering to achieve the same goals at a lower cost” [Fairfax and Whittle 2020: 7].

Beavers are not the only type of animal life that can help in fire management. Ruminants like goats, cows and sheep can control vegetation, while also improving soil health and promoting water retention in well-managed grazing systems. The movement of hoofed grazing animals across grasslands breaks up soil, making it easier for water to infiltrate, while the animal manure provides natural fertilizer.

Another benefit to controlling vegetation through animal grazing is the retention of biomass on the landscape in the form of nourishing manure, rather than clearing it away via logging or burning, for example [Nader 2007]. Grazing also presents opportunities for diversified economic activity within agricultural or silvopasture (the practice of integrating trees, forage, and the grazing of domesticated animals in a mutually beneficial way) systems. In case studies, managed grazing has made farm operations more productive and profitable while at the same time promoting ecological health [Major 2020]. Grazing animals also can increase ecosystem biodiversity[2].

Finally, there is the role of humans and where we choose to live. Part of the reason fires cause such harm to human settlements is because we build houses in fire-prone areas. The wildland-urban interface (WUI) is the site of a large percentage of fires, including particularly destructive fires, and increasing human encroachment of wild areas means that more people are brought into closer range of wildfires, while also negatively impacting ecosystems and their biodiversity. Of course, one bold strategy to reduce fire risk is to change our land use [Syphard 2013].

[2] https://onpasture.com/2017/09/25/biodiversity-through-grazing-management/

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As modern human settlements have expanded, we have designed our fire management strategies to focus almost exclusively on suppression in most places, enforcing a dominant paradigm that fire is always bad and should be eliminated from landscapes. Unfortunately, such policy allows the very buildup of vegetation that can fuel increasingly destructive wildfires.

However, alternative relationships to fire have been practiced across human history, such as the controlled burning used by Indigenous communities across the world, from California to Australia. Recently, the depth of these communities' ecological knowledge is beginning to gain the respect it deserves and to be considered and implemented in mainstream fire practices. In certain circumstances, it is now accepted that controlled burns can help ensure healthy ecosystems by decreasing the destructiveness and frequency of wildfires.

Although the use of prescribed fire is one way to manage vegetation and shape a varied landscape, any strategy that combines fire management and ecological stewardship will be full of site-specific complexity. Thus, it is critical to understand how Indigenous stewardship has been carried out over generations on given landscapes and to factor this knowledge into strategies to combat wildfire and ensure ecological health.

Much of the world’s remaining biodiversity resides in land inhabited by Indigenous groups, whose fire and land management practices come from a deep cultural and spiritual context. That is, “Indigenous fire management is effective in that it is an emergent property of a linked social-ecological system where Indigenous knowledge and culture, and associated livelihoods, are intimately interconnected with landscape management practices” [Mistry 2016: 4].

A path forward into a fire-resilient age might be led by Indigenous groups implementing local, community-owned solutions. Society at large would benefit from supporting and learning from the local communities who have generational knowledge of local ecosystems and fire management. In addition, land stewardship using practices that favor native species, biodiversity, living soils, and aim to retain moisture on the land should be applied on a wide scale. The articles that follow offer detail and insight into these approaches.

Wildfire article summaries

Our burning planet: why we must learn to live with fire, Pyne 2020

Steven J. Pyne is an emeritus professor at Arizona State University and the author of several books on fire history and policy. He wrote this opinion piece as a protest against the prevention and suppression of wildfires in our land management process. He argues that revising our perception of fire and accepting its presence in ecosystems is critical to our ongoing relationship with our planet.

He describes “a paradox at the core of Earth’s unraveling firescapes,” that “we have too many bad fires — fires that kill people, burn towns, and trash valued landscapes. We have too few good ones — fires that enhance ecological integrity and hold fires within their historic ranges” [Pyne 2020]. Operating under a paradigm of total fire suppression leads us astray in managing landscapes, while we so readily accept fire in the form of fossil fuel combustion in so much of our lives. Pyne sees these behaviors as evidence that our relationship with fire is out of whack.

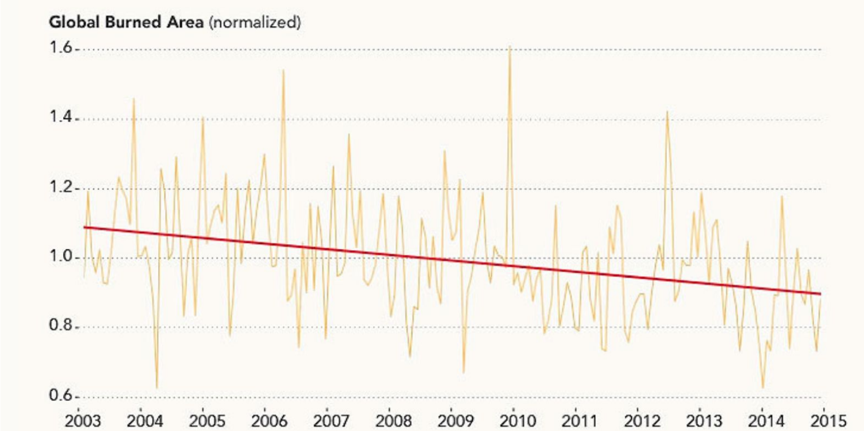
He stresses the importance of distinguishing between burning in living ecosystems and burning the fossils of life from past ages.

> The critical contrast lies in a deeper dialectic than burned and unburned landscapes. It is a dialectic between burning living biomass and burning fossil biomass. We are taking stuff out of the geologic past, burning it in the present with all kinds of little understood consequences, and passing the effluent into the geologic future.
> …
> Fires in living landscapes come with ecological checks and balances. Fires in lithic landscapes have no boundaries save those humans impose on themselves [Pyne 2020].

Pyne associates three paradoxes with our current fire policies. First, abandoning a traditional lore of “light burning” has removed good fires and left us with only bad and harmful ones. When controlled burns are not practiced regularly to manage landscapes, vegetation can build up and fuel the intensity and spread of uncontrolled blazes that spark.

Second and surprisingly: “The Earth does not have more fire today than before fossil fuels emerged as a primary source of energy: It has significantly less” [Pyne 2020]. That is, the amount of land burned in fires has actually decreased, while the presence of intense “feral flames” has increased. The decrease in the scope of fire is largely due to the move away from fire’s use in agriculture and its replacement with modern techniques, including machinery powered by combustion. As Pyne describes, Farmers had relied on fire to fertilize, fumigate, and alter microclimates. Fire did all this in one catalytic process that self-propagated. But with the transition to fossil biomass, modern agriculture found surrogates with artificial fertilizers, pesticides, and herbicides, and it now had the fossil-fuel-powered machines to distribute them. Production became more efficient; transport, more dense. As agriculture joins a modern economy, working flames recede [Pyne 2020].

What we are left with is intense, destructive wildfire, rather than helpful working fire. Pyne points out that we now only see one half of fire's possibilities, since the working fire shaping landscapes and agricultural systems is notably absent. He says: "Landscape fire fades; what fire persists tends to be outbreaks of feral fire. We see those oft-disastrous flames. We don't see the lost fires or the sublimated fires in machines that removed them" [Pyne 2020].



The total area burned globally each year dropped 25 percent between 2003 and 2019. NASA

The third paradox is that as we reduce our use of fossil fuels going forward (as one sort of fire), we will have a greater need "to manage fire in living landscapes." So Pyne calls for us "to reinstate the right kind of fire, and ... adapt to fire's presence and let it do the work for us." He pushes for the recognition that transitioning away from our reliance on fossil fuel burning is an important but incomplete step in balancing ecosystem health. Fires in living systems have an important role to play, and according to Pyne, "the need is not just to reduce fuels to help contain wildfires; those missing fires did biological work for which no single surrogate exists" [Pyne 2020]. He asserts that we will need to reintroduce fire as a staple tool on our landscapes.

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Pyne concludes with a call for the overhaul of our conceptual and policy treatment of fire.

> Anthropogenic fire needs more room to maneuver – more geographic space, more legal space, more political space, more conceptual space. … Equally, society needs to rethink liability law to reduce the risks incurred by fire officers doing a necessary job …; adapt air quality regulations …; and tweak National Environmental Policy Act review processes … [to] accommodate the realities of restored fire at a landscape scale. … Communities in the fire equivalents of floodplains need hardening [Pyne 2020].

He proposes that fire restoration jobs can replace those lost from forestry and fire suppression. He admits that our understanding of fire biology requires more research, and that our greatest need is for “a working fire culture … that ensures fire’s proper place in the landscape” by renewing “our ancient alliance” with fire and making it “an indispensable friend.”

Fire Myths, Hanson 2018

In this podcast interview, Dr. Chad Hanson, an ecologist and fire researcher, shares his perspective on the 2018 wildfires in the American West and some myths that have circulated about fire management in their wake.

First, there is a perception that wildfires in forested regions are so devastating that they reverse the ‘carbon sink’ effect of forests, releasing the carbon of the burned biomass back into the atmosphere. Forests still sequester large amounts of carbon, even if they experience wildfires, because most of the forest remains intact even through blazes. Models that fault wildfires for turning forests into net carbon emitters rest on the assumption that all of the carbon that would usually be stored in a forest is combusted during a fire, but this is far from the reality, in which just a small fraction of a forest’s biomass is consumed. As Hanson says,

> In fact, even in the most intensely burned patches where a fire kills all the trees (which in reality, even in the biggest fires, it's only a small portion, a minor portion of the overall fire)... But even in those areas, only about two or three percent of the above ground

biomass is actually consumed, in other words, ends up as carbon. The trees are still standing there [Hanson 2018].

Second, the intensity of fires has not been universally increasing in recent years. We are experiencing a lot of geographically large fires, but these are not necessarily high intensity fires. The percentage of high intensity fire today is similar to historical precedent, and overall, there is much less fire in our landscapes now than in Earth's geological history. Further, even in the highest intensity fires, forests are never decimated past the point of no return. Trees and vegetation are reestablished after fires, and the ash left behind is dense with nutrients, promoting new growth. Even dead trees, which have long been thought to be responsible for contributing to high intensity fires, are actually not shown to drive fire intensity, according to Hanson.

This series of myths - that forest fires are raging with high intensities, that they burn up so much biomass as to make forests ineffective sources of carbon sequestration, and that the only way to manage forests to avoid these outcomes is to thin out the trees - hinder our understanding of forest management and allow false and harmful solutions to propagate. As a result of these perceptions, proponents of logging have pushed to expand logging operations, purportedly as a fire management strategy. However, according to Hanson, logging is actually linked to greater fire intensity. He explains that small materials, like twigs, are more flammable than trunks.

> Tree *trunks* are not combustible. They really just don't burn. Again, outer bark can burn, but the trees themselves don't burn. What logging does is it removes noncombustible material essentially from the forest and leaves behind very combustible kindling, like slash debris - the branches and small twigs and things like that that are not possible to get up off the forest floor after the tree trunks are removed and that's very combustible.
>
> The other thing that logging does is that it reduces the cooling shade of the forest canopy. By removing a lot of trees, you have more sunlight reaching the forest floor, and what that does is it creates hotter and drier conditions and that means everything on the forest floor gets more dried out, more potentially combustible, and logging also spreads invasive weeds like cheatgrass, which is very, very flammable. Cheatgrass loves a lot of sunlight and so you get a lot of that after intensive logging.
>
> And the last [problem with logging] is a little bit more technical, but basically when you have a lot more trees, it cuts down on the wind speeds that drive fires. It has a buffering effect in a sense. And when a lot of the trees are removed, that buffering effect is reduced or eliminated and fire spreads through those forests faster [Hanson 2018].

This three-fold effect of logging makes forests more vulnerable, and it is important to dispel the concept that removing trees is the best way to keep people safe from fires. Hanson criticizes the opportunism of using these fire myths to advance an agenda of logging. He cautions that when fire science and policy emerge from the U.S. Forest Service, which manages national forests and gains a good deal of revenue from logging, there is a perverse incentive to keep practicing logging as fire management. He calls for clearer and more public communication from scientists to dispel fire myths and share recent findings that have been shifting so much of what we know about fire science.

Hanson says that the best strategy to ensure the protection of homes from wildfire is to focus on the homes themselves. This can be done by using fire resistant building materials, fire-proofing roofs, erecting rain gutter guards to prevent the accumulation of small fuels like pine needles, pruning the vegetation in a 100-foot radius of a house, and removing small shrubs and branches of mature trees, while leaving those trees standing. Fire management interventions at this level are shown to be far more effective at preventing damage than attempts to control the fuel load of fires within forests.

Hanson points out the need to decouple fires that occur in remote forest ecosystems and those that rage through human settlements and urban communities, because thinning out vegetation in attempts to suppress the former do not actually protect against the latter. In fact, thinning forests undermines the ecological processes that fire serves in forest systems. When discussing fires that have devastated homes and lives, he says

> I mean, where's the forest in Malibu? There's no forest. These are chaparral ecosystems, most of the fires that are burned homes and lives have been lost are not in forest. In fact, they're mostly nowhere near forests. They're in grasslands, chaparral shrub habitat, oak woodlands. But the areas that are in forest, where we've had tragic loss of homes and lives, these are mostly areas where we've had intensive logging, and it's like I mentioned earlier, you know, more logging is typically associated with more intense fire at a faster rate of spread. [Hanson 2018]

He advocates for a greater focus on fire prevention around homes and communities themselves, in what is known as 'defensible space.' He points out that such measures are a great source of jobs, as well as an effective intervention curbing the destructiveness of fires. With a shift in focus from forest thinning to fire-proofing, and better understanding and communication of fire science, we can let go of some of the fire myths that have been dictating policy and failing to meet public needs.

> More logging is typically associated with more intense fire at a faster rate of spread [Hanson 2018].

Land use planning and wildfire: development policies influence future probability of housing loss, Syphard et al. 2013

Wildfire is a challenge that threatens human settlement at an increasing scale, but planning and development does not always address this threat. In fact, policy around land use is in large part responsible for the destruction of homes and property and the threat to human life that occurs in wildland-urban interfaces (WUIs). While there is much literature on how to suppress fires, mitigate their damage, or manage for less destructive fire seasons, a more far-reaching strategy would be to stop building in fire prone areas. Land use decisions can be improved to lessen the risk of infrastructure loss and foster healthy ecosystem function.

> Land use planning is an alternative that represents a further shift in thinking, beyond the preparation of communities to withstand an inevitable fire, to preventing new residential structures from being exposed to fire in the first place. The reason homes are vulnerable to fires at the wildland-urban interface is a function of its very definition: “where homes meet or intermingle with wildland vegetation”. In other words, the location and pattern of homes influence their fire risk, and past land-use decision-making has allowed homes to be constructed in highly flammable areas. [Syphard 2013: 1-2]

In many areas, including in California, we have come to expect fire, but have not necessarily learned to live with it. The authors of this study analyzed what types of human development carried out in the next several years might contribute to or avert the risk of fire damage. They examined the South Coast Ecoregion of San Diego County, which they describe as:

> topographically diverse with high levels of biodiversity, and urban development has been the primary cause of natural habitat loss and species extinction. Owing to the Mediterranean climate, with mild, wet winters and long summer droughts, the native shrublands dominating the landscape are extremely fire-prone [Syphard et al. 2013: 2].

This study acknowledges the responsibility humans have in shaping the landscape and its biodiversity, and in contributing to fire activity by building into wild areas and expanding WUI. They sought to understand how patterns of development and housing density might influence future fire spread and intensity. They found that

> structures in areas with low- to intermediate- housing density were most likely to burn, potentially due to intermingling with wildland vegetation or difficulty of firefighter access. Fire frequency also tends to be highest at low to intermediate housing density, at least in regions where humans are the primary cause of ignitions [Syphard 2013: 2].

Though it is impossible to reverse the effects of policies that have shaped the fire landscape we have today, understanding the way human behavior contributes to our own risk of harm from wildfire can help us plan intelligently going forward. The authors conclude that

> With projections of substantial global change in climate and human development, we recommend that land use planning should be considered as an important component to fire risk management, potentially to become as successful as the prevention of building on flood plains. History has shown us that preventing fires is impossible in areas where large wildfires are a natural ecological process. As Roger Kennedy put it, "the problem isn't fires; the problem is people in the wrong places [Syphard 2013: 10-11].

Community owned solutions for fire management in tropical ecosystems: case studies from Indigenous communities of South America, Mistry et al. 2016

Indigenous groups across the world have developed ecological knowledge linked to the places they inhabit, including prescribed fire practices used to maintain healthy ecosystems. Mistry et al. examine the challenges Indigenous communities in South America face in managing the landscape through fire and preserving such knowledge across generations in sometimes hostile political climates. However, there is growing recognition that Indigenous people have a vital role to play in combating climate change and supporting biodiversity and healthy ecosystems.

> Emerging research shows the fundamental role of Indigenous land-use practices for controlling deforestation and reducing CO_2 emissions—analysis of satellite imagery suggests that Indigenous lands have reduced rates of deforestation and habitat conversion, and lower greenhouse gas (GHG) emissions, compared with surrounding areas [Mistry 2016: 1].

While indigenous groups' use of prescribed fire early in the dry season to prevent destructive out-of-control fires is gaining broad recognition, that hasn't necessarily translated into greater respect or autonomy for those communities. Instead, Indigenous people may be given auxiliary roles in fire management, or have their knowledge utilized but implemented by non-local organizations in structures that fail to benefit or empower the local communities themselves. While this may still achieve desired wildfire management results, it weakens intergenerational knowledge transfer and undermines the social and spiritual role of prescribed fire within communities.

Mistry et al. argue that "Indigenous fire management is effective in that it is an emergent property of a linked social-ecological system where Indigenous knowledge and culture, and associated livelihoods, are intimately interconnected with landscape management practices" [Mistry 2016: 4]. Precisely because prescribed fire matters to Indigenous communities as something more than a tool in the toolkit of managing wildfires, it is effective when carried out by those communities in reducing risk of destructive wildfires and supporting healthy and biodiverse ecosystems.

> Importantly, the numerous uses of fire mean that burning is a relatively constant activity, particularly during the dry season, generally at low levels, thereby helping to prevent the build-up of flammable fuel and incidents of large-scale uncontrollable wildfires. Experimental studies of fire behaviour suggest that this patch mosaic burning not only reduces the occurrence of dangerous fires, but also increases spatial and temporal vegetation heterogeneity and biodiversity [Mistry 2016: 4].

These authors distinguish between Indigenous relationships to ecosystems and market-based approaches to ecosystem services valuation, which attempt to incentivize conservation through payment. While the goal of the market-based approach is to monitor and preserve functioning ecosystems, “their ideological foundations within a neoliberal agenda that promotes ‘selling nature to save it’ is in stark contradiction with Indigenous ontologies based on human–nonhuman–spiritual relationships” [Mistry 2016: 2].

Within Indigenous communities, fire plays a role in social bonding, intergenerational knowledge transfer, and agricultural practices. Mistry et al. argue that

> savanna and forest ecosystems are being protected within Indigenous lands not because they are being ‘managed’ in a direct and active way, but as the indirect outcome of a healthy social–ecological system, i.e. the outcome of practices that maintain social and ecological integrity, or what can be termed ‘community owned solutions [Mistry 2016: 4].

But challenges, including loss of fire knowledge by younger generations within Indigenous groups because of outside pressures and encroachment, pose a threat to these fire management practices. For example, in Venezuela and Brazil,

> young Wapishana and Makushi and some community leaders were more critical about the use of fire as they had more regular contact with state natural resource management officials and environmental organizations that promoted antifire discourses. As with the Krahô, changing Indigenous values to focus on fire prevention and suppression could have the effect of making the problem worse [Mistry 2016: 4].

That is, when prescribed burning is taken out of its original context and represented to younger generations of Indigenous people and land stewards as simply a well-incentivized tool, the

Indigenous communities themselves are diminished, along with the robustness of their ecological knowledge that gets passed forward.

In spite of lingering antagonistic views in Brazil and Venezuela toward indigenous fire management, attitudes are changing.

> Not only is there a move away from categorizing all fire as ‘bad’; there is also a recognition that Indigenous fire knowledge is a valid form of knowledge that could inform policy-making [Mistry et al. 2016: 6].

Mistry et al. suggest the best way to achieve both ecological and communal health might be through power-sharing arrangements. By empowering Indigenous communities, national governments could in turn work toward their fire management and biodiversity conservation goals. This might require evaluating ecological health in ways beyond just quantitative metrics, which reduce these complex systems down to a set of standardized numbers, as well as the recognition that the well-being of these ecosystems is tied to the Indigenous communities that inhabit them, according to the authors:

> There needs to be enabling policies that focus on legitimizing and strengthening Indigenous fire management as a community owned solution. Critically, as community owned fire management is intricately linked with Indigenous survival strategies, so too must firefighting and prescribed burning be grounded in local social–ecological systems. We believe it is necessary to define long-term actions to support the integrated functioning and survival of Indigenous communities as a whole, rather than focusing on isolated issues (e.g. carbon retention) or benefits for some individuals (e.g. hiring Indigenous firefighters) [Mistry 2016: 8].

This systems approach may well be the key to successful long-term fire management. The authors offer this challenge:

> What we want to do is not promote one over the other, but encourage decision-makers to engage with, and appreciate, Indigenous perspectives and worldviews on fire management. Community owned solutions acknowledge collectivity, spirituality, process orientation and locality, whereas many expert-led fire management interventions often result in promoting individualism, ethnocentrism, rationality, efficiency, commercialism and globalization. The question we raise is this: can the ‘community owned solutions’ approach be the mechanism through which Indigenous perspectives can be represented within fire management [Mistry et al. 2016: 8]?

Invasive grasses increase fire occurrence and frequency across US ecoregions, Fusco et al. 2019

It has long been suspected that the increasing abundance of invasive grass species may contribute to wildfires in the United States by adding abundant new fuels to ecosystems, increasing the range of conditions that lead to fire ignition, and enabling the development of larger, hotter fires. The new fire regimes (patterns of fire duration, intensity, and spread) that emerge can in turn destabilize wildlife and lead to local extinctions while expanding favorable habitat for the invasive species, for many of these grasses recover quickly after fires, providing renewed fuel and potentially increasing the frequency of fires.

The authors of this paper provide a comprehensive analysis on the impact of 12 non-native grasses on the occurrence (whether a fire occurred in a particular place), frequency (how many times a place burned), and size of wildfires. The research was conducted across 29 US ecoregions, including deserts, temperate forests, wetlands, woodlands, river valleys, shrublands, and coastal plains. Data were collected and combined from fire records and records of invasive grasses, and results from “invaded” regions and nearby “uninvaded” regions were compared. The authors also considered human activities and ecological factors related to fire.

> One of the most notorious impacts of nonnative, invasive grasses is the alteration of fire regimes. Yet, most evidence of these impacts comes from local-scale studies, making it unclear whether they have broader implications for national and regional fire management. Our analysis of 12 invasive grasses documents regional-scale alteration of fire regimes for 8 species, which are already increasing fire occurrence by up to 230% and fire frequency by up to 150%. These impacts were demonstrated across US ecoregions and vegetation types, suggesting that many ecosystems are vulnerable to a novel grass-fire cycle. Managing existing grass invasions and preventing future introductions presents a key opportunity to remediate the ecological and economic consequences of invasive species and fire [Fusco 2019: 23594]

The results of this analysis showed that 8 of the 12 invasive grass species examined were associated with significantly higher fire occurrence and fire frequency, and that fire occurrence more than doubled for two of these species. Three of the species did not impact fire occurrence, and a decrease in fires was associated with one species (a wetlands grass species). The impact on fire size was variable, with two species associated with larger fires, three species associated with smaller fires.

> Individually, climate change is expected to increase the potential for fire occurrence by 150% by the end of the century based on projected changes in temperature and precipitation. Here we show that 8 invasive grass species are already associated with increased rates of fire occurrence by 27 to 230%, and 6 invasive grass species are

> associated with increased mean fire frequency by 24 to 150%, compounding current and future fire risk across the United States. [Fusco et al. 2019: 23595]

The authors suggest that fire and invasive species managers work together to create integrated management plans; otherwise, the convergence of human activities, climate change, and invasive species will continue to promote wildfires across the United States.

Smokey the Beaver: beaver-dammed riparian corridors stay green during wildfire throughout the western USA, Fairfax and Whittle 2020

This study examines the positive effects of beaver damming on the resistance of landscapes to wildfire damage. The authors find that in riparian corridors (areas along rivers), the presence of beavers and their dams can create refuges that withstand blazes that consume surrounding vegetation.

Beavers play an important role in wetland habitats and are known as ecosystem engineers for the way they can shape landscapes with their activities. Beaver dams slow down water moving across a landscape, holding it in place for longer and allowing water to infiltrate into the soil, which raises water tables.

> The combination of building flow obstructions (dams), accumulating water (ponds), and spreading that water out in the landscape (channels) gives beavers the unique potential to modulate environmental extremes such as flood and drought. When it comes to water, beavers slow it, spread it, and store it.
>
> Due to the fact that beaver channels and dams spread water out in the landscape and store it broadly in adjacent soils, the vegetation near beaver ponds doesn't experience as much reduced water availability during drought. Drought-stricken vegetation burns more easily than lush, green vegetation, so it follows that the vegetation around beaver ponds would be more difficult to burn than vegetation around undammed creeks [Fairfax and Whittle 2020: 1].

Fairfax and Whittle observed the effects of beaver dams on preventing fire spread to the areas where they had built dams, examples of which are shown in satellite imagery below.

The authors quantify the effects of beaver activity in fireproofing areas by examining the Normalized Difference Vegetation Index (NDVI) observed in satellite imagery before, during, and after wildfire years in the American West. They found that while vegetation is able to reestablish itself a year after fire damage regardless of beaver activity due to its own resilience to fire, areas in beaver dammed zones maintained vegetation even during wildfires, demonstrating actual resistance to blazes, not just the ability to recover after damage. They note how vital this is for those ecosystems and the life within them.

> These ribbons of fire-resistant riparian corridor may be particularly important for species that are unable to physically escape wildfire. They can provide temporary habitat for fish, amphibians, reptiles, small mammals, wild and domestic ungulates, and birds that are unable to outrun/outfly the spread of flames. While we found that beaver activity does play a significant role in maintaining vegetation greenness during wildfires, it does not appear to play a significant role in the ability for a riparian corridor to rebound in the year following fire. Riparian vegetation NDVI rebounded in the year following the fire regardless of proximity to beaver activity. Thus, we would describe beaver activity as creating refugia during wildfire, but not necessarily changing the long-term landscape outcomes [Fairfax and Whittle 2020: 7].

The survival of wildlife is crucial to these ecosystems, and beaver activity uniquely contributes to the creation of refuge areas that resist burning and can provide shelter for animals during these destructive events. The authors conclude,

> As it stands today, wetland habitat is very limited and beavers can create and maintain wetland habitat that persists through flood, drought, and, as we have shown in this study, fire. This has immediate relevance to scientists and practitioners across North America and Eurasia, particularly in places with increasing wildfire risk and existing or planned beaver populations. Perhaps instead of relying solely on human engineering and management to create and maintain fire-resistant landscape patches, we could benefit from beavers' ecosystem engineering to achieve the same goals at a lower cost [Fairfax and Whittle 2020: 7].

Planned Herbivory in the Management of Wildfire Fuels, Nader et al. 2007

Nader et al. survey herbicides, prescribed fire, mechanized treatments, hand cutting, and grazing animals as fire management techniques. Managing vegetation involves "changing the plant community to decrease the flame height when fire occurs," favoring native species that may be more resilient to fire, and altering the landscape to create fuel breaks, which are patches across which it is hard for fire to jump [Nader 2007: 18].

Focusing their analysis on grazing and the contexts in which it is most useful, the authors note that there are many site and animal specific factors to take into account for successful implementation.

> [Grazing] is a complex, dynamic tool with many plant and animal variables, and it requires sufficient knowledge of the critical control points to reach treatment objectives. Those control points involve the species of livestock grazed (cattle, sheep, goats, or a combination); the animals' previous grazing experience (which can affect their preferences for certain plants); time of year as it relates to plant physiology (animal consumption is directed by the seasonal nutrient content); animal concentration or stocking density during grazing; grazing duration; plant secondary compounds; and animal physiological state [Nader 2007: 19].

Grazing has the advantage of keeping nutrients in the ecosystem, unlike mechanical methods that harvest vegetation to be sold as biomass chips (like wood chips). This means that when animals digest vegetation and excrete on the landscape, they participate in the local nutrient cycle. Animals also trample soil, which can crush fine fuel and mix it into the soil, where it cannot contribute to ignition, which reduces one contributing factor to persistent and destructive blazes. Animals do more than just remove extra vegetation – they can have many beneficial interactions within a given ecosystem.

> Any grazing plan designed for fuel reduction needs to consider the grazing impacts on parameters other than just simply reduction. The effects of the grazing management should be studied for their impact on water quality, compaction, riparian vegetation, disease interaction with wildlife (bluetongue, pasturella), and weed transmission. The positive aspects of grazing over other treatments also should be weighed, including recycling of nutrients into the products of food and fiber [Nader 2007: 22].

By introducing grazing animals into a landscape or agricultural system, managers can affect biodiversity in complex ways. The authors mention that "Hadar et al. reported that light grazing increased plant diversity on treated sites. Thus, when proposing a stocking rate for treatment consumption, the environmental impact needs to be considered" [Nader 2007: 22].

Nader et al. conclude that "grazing is best used when addressing vegetation with stems of smaller diameters that make up the 1- and 10-hour fuels. These two fuel classes are important because they can greatly impact the rate of spread of a fire, as well as flame height" [Nader 2007: 19]. While they call for further research to validate anecdotal accounts supporting grazing and understand its best practice, they maintain that "prescribed grazing has the potential to be an ecologically and economically sustainable management tool for reduction of fuel loads" [Nader 2007: 20].

Landscape rehydration 'better than dams' in improving farm production, reducing fire risk, Major 2020

A project in Queensland, Australia has met with success in its efforts to rehydrate the landscape on the farmland property of Worona Station, improving biodiversity, water retention, and resistance to erosion and fire. Worona Station had been degraded and faced serious erosion issues, so Chris Le Feuvre, the owner, partnered with consultancy groups of NQ Dry Tropics and the Mulloon Institute in a project to rehydrate his land.

The project team has used a combination of planned grazing and small, low-tech dams to combat erosion problems. The grazing technique involves:

> Splitting paddocks into small sizes and using large mobs of cattle grazing on rotation ... grazing pasture more intensively while giving it longer to rest, [thereby] increasing carrying capacity.

Grazing in this way (which is evocative of Allan Savory's Holistic Planned Grazing methodology) has resulted in increased pasture species diversity and boosted plant growth, allowing the Le Feuvre to double his herd size. Planned grazing has also reduced sediment runoff from the property. Sam Skeat, a grazing officer with NQ Dry Tropics, attests to the importance of grazing.

> The plug-and-pond technique — also known as leaky weirs — involves small dam-like structures to lift the bed level of the water, which is then run onto the floodplain to grow pasture and recharge aquifers. While weirs have been strategically constructed, Mr. Skeat said grazing management was the most important tool to improve water retention in a landscape. 'If you can use cattle as a tool to regenerate the grassland, you'll get more infiltration, slow the flow, hold water up in the landscape and have you growing grass for longer' [Major 2020].

Rehydrating landscapes can improve their resilience to extreme events, and improve their quality in the face of chronic problems like erosion. According to the Mulloon Institute Chairman Gary Nairn, the issue of degraded gullies and streams is a national concern. Gullies are created when parched land is unable to absorb rainwater, allowing it to run off. The sediment-filled runoff ends up in the ocean, polluting it.

Nairn sees land rehydration through planned grazing and related techniques as a better solution than building a massive, industrial-scale dam to retain water. The Australian government has been looking into building new large dams. Levels at Warragamba Dam, which supplies about 80 percent of Sydney's water, have dropped to less than half capacity.

> 'We've been able to demonstrate in Mulloon, if we repaired and rehydrated the catchment through to the Sydney water supply, you could store the equivalent of Warragamba Dam,' he said [Major 2020].

Well-watered mulberry tree credited with saving home on NSW South Coast from summer bushfires, Aubrey 2020

A well-watered mulberry tree has been credited with averting the danger of destructive wildfires from destroying Brett Hawkins' home during 2020's unprecedented fire season in Australia. When massive fires raged through the bush through the summer, many homes were completely engulfed. However, Hawkins attested that when he returned to his home after evacuating,

> 'I could see straight away the house was intact — the roof was intact, but everything else around it was burnt, with the exception of the mulberry tree.' He described the stark scene greeting him upon arriving back home, 'It was apocalyptic,' Mr. Hawkins said. 'There was not a tree left, ash on the ground and smouldering embers everywhere.' But among the blackened trees, Mr. Hawkins found his mudbrick house and mulberry tree in full leaf [Aubrey 2020].

In the season's drought, he had been rationing water, but sparing some to keep his tree hydrated and healthy, which may have been a contributing factor in its resistance. According to the article, "Mr. Hawkins believed that by heavily watering the tree, combined with luck regarding which direction the fires came, the full heat of the bushfires was shifted." [Aubrey 2020]

Another important feature is the mulberry's lack of dried leaves and brush at its base that might pose a danger of igniting. Other species, like eucalyptus, with oily leaves that could dry out, or pine trees whose long branches catch dry leaves, are less ideal.

A tree expert from the Fenner School of Environment at the Australian National University analyzed some of the possible factors leading to the survival of this mulberry tree and what it might teach those wishing to fortify the fire resilience of their homes and properties. "While there does not seem to be a clear answer on what to plant to 'fire-proof' your house, Professor Brack said a well-watered tree, with a clear trunk and no loose, dry leaves or branches is a good start" [Aubrey 2020].

Ecological corridors and connectivity

Establishing ecological corridors is a way to mitigate the effects of habitat loss and fragmentation. Ecological corridors are linear landscape elements connecting otherwise isolated habitat patches within a larger matrix of environmentally degraded lands (urban or agricultural, for example). The corridors facilitate gene dispersal and migration, while also expanding habitat range for species constrained by patch size. They can take the form of riparian (river) ecosystems, hedge networks, forest edges, or grassy bands.

Ecological (wildlife/biological) corridors are based on the concept of connectivity, which is essential to ecosystem functioning, and thus to the persistence of life on earth. When connectivity is disrupted, so are “ecological processes such as gene flow, pollination, [and] wildlife dispersal” [Estreguil 2013: 5]. Dinerstein et al. [2020] recommend establishing a global safety net against the intertwined threats of climate change and biodiversity loss. For this, they suggest the protection of 50% of land surface as intact, interconnected ecosystems.

The field of conservation has recently integrated the idea of connectivity, thus moving beyond efforts to simply set aside protected patches. Beginning in the 1990s, the study of ecological corridors has investigated their effect on biodiversity, their traction in the realm of public policy, and strategies for mapping corridors. Most studies show that ecological corridors are indeed effective in protecting species, although some species benefit more than others, depending on corridor design. Achieving political salience for such initiatives, however, appears to be as difficult as for any other conservation project.

Nevertheless, the mapping and development of ecological corridors is a way to enter into conversation with multiple stakeholders about conservation and the potential for collaboration. While establishing large protected areas often falls under the jurisdiction of national governments, restoring strips of land to connect these areas is well suited to the work of communities, local planners and public and private land managers. Within a regional, national or international context, establishing a network of connected ecosystems calls for coordination at multiple levels of government.

In 2009, the French government encoded the idea of ecological corridors into law, thus initiating a process for mapping out degraded areas and those with higher levels of ecosystem intactness. In collaboration with local and national actors, each regional government engaged in a process of mapping out land, whether public or private, where ecosystems are in relatively good condition and should be preserved, and where land is in poor condition and should be restored. The maps also include potential ecological corridor routes.

The combining of the regional maps into a whole country map thus creates a coherent ecological framework for land protection and restoration efforts. It is a tool to help local and regional planners prioritize conservation efforts in the places likely to best protect wildlife and ecosystem processes. While urban planning documents are expected to take these maps into account, the manner and extent to which ecological concerns are weighted in urban planning decisions is subject to local interpretation. Thus, the maps can serve as a tool for those motivated to protect the environment, yet they remain easily sidelined by the less motivated.

In their 2019 assessment of French ecological corridor efforts, Chaurand & Bigard suggest that part of the reason corridor development has not been more readily adopted at the local level is that much of the knowledge and enthusiasm for the idea exists at the national level among researchers and program leaders. To remedy this, they recommend investing in a system to relay information between local and national actors.

Similarly, critiques of the MesoAmerican Biological Corridor (MBC) have noted the shortcomings of a top-heavy approach [Dettman 2006, Grandia 2007, Harvey 2007, Beauvais & Matagne 1999]. Funded by the World Bank and led largely by international conservation organizations, development of this ecological corridor appears not to have effectively partnered with nor sought adequate input from local communities.

Consequently, the MBC has met with limited success in terms of biodiversity conservation. Connectivity for nine mammals in the Panama portion of the MBC is already severely fractured and predicted to decline further with planned road construction and other development projects on the horizon. In light of these findings, the authors of a Panama study [Meyer 2019] are not particularly optimistic about the condition of ecological connectivity in the MBC overall.

On a brighter note, Belize has recently approved a plan under the rubric of the MBC to establish a 110 km^2 ecological corridor, which will be one of Central America’s largest. This was the outcome of collaboration between landowners, government and NGOs. South of the MBC, another ecological corridor is being developed in Brazil [Zanon 2020]. Thanks to the work of a local NGO that combines conservation with local community education, additional corridors will create a total of 44,920 ha^2 of connected habitat. This is expected to increase the population of the threatened target species (black lion tamarin) by 30%.

These two examples notwithstanding, it is ironic that ecological corridors (designed to mitigate the effects of habitat destruction) are subject to the same pressures and obstacles as the problem they aim to remedy. Difficulty stems from the multiplicity of economic interests in land and a mosaic of ownership titles across a given landscape. Furthermore, the ecological concept of connectivity is not necessarily understood by the general public or policy makers, resulting in its low ranking as policy priority.

The ecological concept of connectivity is not necessarily understood by the general public or policy makers, resulting in its low ranking as policy priority.

The European Natura 2000 network, which helped spur France's ecological corridor mapping initiative, is a continent-wide network of natural or semi-natural areas. However, the vast majority of these sites (86%) are unconnected to one another [Estreguil 2013], a fact which severely limits their value to wildlife. In spite of covering 18% of the land area of Europe, the nearly 28,000 sites in the network are isolated islands of nature within a generally hostile surrounding landscape.

> There is the need to acknowledge nature as a system rather than individual parts. The establishment of N2K [Natura 2000] network (i.e. the sum of the individual sites) should be distinguished from the establishment of the overall ecological coherence of the network [Estreguil 2013: 5].

Furthermore, the areas themselves are not formally protected and can theoretically be developed; however, they are less likely to be developed by virtue of being a Natura 2000 site. A 2018 EEA assessment suggested that to "unlock" the potential of this ecological network, biodiversity policy should be thoroughly integrated by member states with economic development and other public policy domains, and that greater stakeholder engagement should be sought such as through citizen science biodiversity monitoring initiatives.

The enormous potential of ecological corridors fully depends on concerted efforts to communicate the meaning and importance of connectivity to stakeholders at every level of government and within the general public.

> There is the need to acknowledge nature as a system rather than individual parts [Estreguil 2013: 5].

Ecological corridor article summaries

A "Global Safety Net" to reverse biodiversity loss and stabilize Earth's climate, Dinerstein et al. 2020

Currently, 15.1% of land on Earth is conservation protected. This article maps out an additional 35.3% of land needing near-term protection, along with ecological corridor routes connecting these areas. Half of the planet's land is needed to serve as a Global Safety Net to biodiversity loss and stabilize the global climate.

> While the parallel crises of biodiversity loss and climate change have generally been approached separately, a key solution for two of the most pressing challenges of our time is the same: conserve enough nature and in the right places [Dinerstein 2020: 1].

The "right places" were identified by mapping areas with rare or endangered species, biodiversity hotspots[3], and places with distinct species assemblages. Onto this, the authors mapped areas where wild large mammals are still able to range widely and freely, a phenomenon that has become rare globally given the extent of anthropogenic land conversion, and areas of remaining intact wilderness.

The study also maps out a system of wildlife corridors to connect conservation areas. Only half of currently protected areas are connected. "Connecting all current terrestrial protected areas via potential wildlife and climate corridors (using 2.5 km as an average corridor width) adds 5,705,206 km2 or 4.3% of the terrestrial realm" [Dinerstein 2020: 4]. Assuming the additional lands identified in this study for conservation are formally protected, the amount of land needed for connectivity would be significantly reduced.

While large conservation protections require national leadership to achieve, the need to establish connectivity presents a role for local and regional actors to restore degraded lands in their midst.

> The connectivity analysis offers a template to build from and engage local and regional entities in designing programs centered on restoring connectivity. This effort could merge with global habitat restoration and native tree-planting initiatives now under way [Dinerstein 2020: 7].
>
> Focusing restoration efforts on degraded lands that can serve as wildlife corridors could help achieve other objectives, such as the Bonn Challenge. Similarly, massive tree-planting programs, if designed using native species and planted to restore corridors, riparian and coastal vegetation, and upper watersheds, could contribute to stabilizing climate and restoring connectivity [Dinerstein 2020: 7].

At the national level, countries could use the Global Safety Net framework to map out their own corresponding national safety nets. The 20 countries with the greatest role to play in establishing the Global Safety Net include: Russia, Brazil, Indonesia, the United States, Costa Rica, Peru, and Namibia.

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[3] A biodiversity hotspot is a place that is rich in biodiversity, yet threatened. To qualify, a region must be home to at least 1,500 plant species found nowhere else in the world and have lost at least 70% of its original extent of habitat cover. Currently, there are 36 global biodiversity hotspots, according to the Critical Ecosystem Partnership Fund (https://www.cepf.net/our-work/biodiversity-hotspots/hotspots-defined).

> Investments needed for the establishment and management of additional protected areas and restoration of degraded lands, while substantial, are small compared with enormous fossil fuel subsidies. The estimated $4.7 trillion per year in fossil fuel subsidies are expected to decline as the Paris Climate Agreement is implemented, making government resources available for restoring, rather than destroying, our global climate system [Dinerstein 2020: 7].

The authors emphasize that the conservation goals of the Global Safety Net are achievable, especially if indigenous people's land rights are honored. One third of land identified for a Global Safety Net is managed by indigenous communities in a way that preserves biodiversity and regulates Earth's atmosphere.

Guidelines for conserving connectivity through ecological networks and corridors, Hilty et al. 2020

The International Union for Conservation of Nature (IUCN), which created these guidelines, is an international environmental network founded in 1948 that provides conservation data, assessment and analysis to governments, NGOs and private entities. IUCN also manages the Red List of Threatened Species. This connectivity guideline is part of a series of best practices for protected area land managers.

Providing a definition and context for the importance of connectivity, the authors state:

> 'Ecological connectivity' is the unimpeded movement of species and the flow of natural processes that sustain life on Earth. This is not an overstatement. Without connectivity, ecosystems cannot function properly, and without well-functioning ecosystems, biodiversity and other fundamentals of life are at risk [Hilty 2020: xii].

Moreover,

> Most global, regional and national targets for biodiversity conservation, climate change and environmental sustainability cannot be met unless ecological connectivity conservation is addressed [Hilty 2020: 48].

In short, ecological connectivity undergirds the conditions for life on Earth. The authors explain that the concept of connectivity reflects an evolution in conservation science. Previously, nature conservation consisted primarily of setting aside areas of undisturbed or minimally disturbed land. While protected areas remain the foundation of nature conservation, "they are no longer considered sufficient in many places. It is now understood that active measures must also be taken to maintain, enhance or restore ecological connectivity among and between protected areas and OECMs[4] [Hilty 2020: 2].”

Hence,

> These Guidelines have been drafted to help clarify and standardize a shift in conservation practice from a narrow focus on individual protected areas to considering them as essential parts of large landscape conservation networks. This is done through creating ‘ecological networks for conservation’ that are specifically designed, implemented and managed to ensure that ecological connectivity is maintained and enhanced where it is present, or restored where it has been lost. Unless systems of protected areas and OECMs retain all essential ecosystem processes, they are not sufficient [Hilty 2020: 3].

The guidelines emphasize the importance of clearly defining one or more ecological objectives for establishing a corridor, such as to facilitate gene dispersal, migration, or adaptation to climate change for particular or multiple species. Clearly defined objectives allow for a corridor to be created in a way that leads to successful outcomes vis a vis the objectives. Primary objectives should relate directly to ecological connectivity, while complementary social or economic objectives (ecosystem services, such as flood and erosion control, enhancing crop pollination, for example) may also be included.

> The toolbox for connectivity conservation includes various types of formal and informal recognition, national legislation, local and regional zoning regulations, conservation easements, conservancy design and transportation planning [Hilty 2020: 48].

The importance of connectivity is increasingly recognized in international treaties, and in national and sub-national planning and policy initiatives.

> Until recently, connectivity legislation was rare at the national or even sub-national level. Now, countries such as Bhutan, Costa Rica and Tanzania, and sub-national jurisdictions such as California and New Mexico (USA), have enacted corridor legislation. Additionally, site-specific legislation has been enacted in some countries. For example, the South Korea Act on the Protection of the Baekdu Daegan Mountain System, 2003 (Act no. 7038), which came into effect in 2005, designates an area of 263,427 ha. Of this, 86% is made up of 183 existing protected areas and 14% consists of new buffer

[4] OECM stands for “other effective area-based conservation measures,” which refers to: “a geographically defined area other than a protected area, which is governed and managed in ways that achieve positive and sustained long-term outcomes for the in situ conservation of biodiversity with associated ecosystem functions and services and, where applicable, cultural, spiritual, socio-economic and other locally relevant values are also conserved [Hilty 2020: 50].

> and core areas that create a biodiversity corridor along the main mountain range of the Korean Peninsula [Hilty 2020: 45].

However, mostly countries have not yet effectively integrated connectivity into policy and planning. Partly this is due to the complexity of establishing ecological corridors.

> Connectivity conservation requires innovative implementation approaches to conserve lands and water within the conservation matrix – across patterns of resource use, jurisdictions, cultures and geographies [Hilty 2020: 48].

These guidelines are meant as a toolbox to help local, regional, national and international entities navigate that complexity.

> ‘Ecological connectivity’ is the unimpeded movement of species and the flow of natural processes that sustain life on Earth. This is not an overstatement. Without connectivity, ecosystems cannot function properly, and without well-functioning ecosystems, biodiversity and other fundamentals of life are at risk [Hilty 2020: xii].

Constructing ecological networks based on habitat quality assessment: a case study of Changzhou, China, Gao et al. 2017

Changzhou is a city near the Yangtze River delta on the east coast of China that has undergone extensive urban development. “From 2006 to 2014, the built-up area in the city increased by 25.68%” [Gao 2017: 2]. This study is part of an effort to boost biodiversity and ecosystem services in the city, which, at the time of the study, had a few protected patches but no corridors connecting them.

The authors identified potential corridors by comparing three different methods for assessing the level of resistance wildlife would face in moving across the landscape from one habitat patch to another. Corridors were identified by mapping out the paths of least resistance. Potential corridors consisted mainly of riparian greenspaces, followed by forest and farmland, and included between 3.45% and 16% built-up space, depending on the method used. Corridor width was assumed to be 30m. Connection of the most important protected patches should be prioritized in corridor construction.

Integrating priority areas and ecological corridors into national network for conservation planning in China, Liang et al. 2018

In contrast to the Gao et al. [2017] article (above), this study maps out an ecological network spanning the entire nation of China. Most such ecological corridor analysis has previously focused at the local and regional levels, according to the authors. They note that in addition to protecting biodiversity, ecological corridors (ECs) purify air, regulate climate, and "realize the movement of material, energy, and information in the ecosystem" [Liang 2018: 23].

This study identifies a couple of dozen high priority areas for conservation based on the existing diversity and quality of the landscape. These high priority areas encompassed seven ecotones (broadleaf forest, coniferous forest, shrub, herbaceous plant, sparse vegetation, wetland, water body), while built up areas such as cities were low priorities. The authors mapped these conservation priority zones against existing formally protected areas (which cover 15% of the country), finding only 19% overlap and, thus, revealing extensive conservation gaps.

> The majority of China's nature reserves were established without a clear planning framework, and couldn't maximize efficiency of conservation targets. … important zones for species migration are not considered as conservation goals in the current nature reserve system [Liang 2018: 26].

The ecological corridors were identified by examining the pathways with the least amount of potential resistance (such as built infrastructure) to animals moving along them. The shortest routes were not necessarily chosen given the need to bypass urban areas. The map created through this study offers useful information for national conservation planning.

> From a long-term conservation perspective, in view of the rapid habitat loss and biodiversity reduction, the ecological network represents a valuable tool to protect the biotope[5] and their ecological functions in China. In this regard, our results show the importance and need to develop a national protection network maintaining connectivity among them in order to achieve high cost efficiency [Liang 2018: 27].

A meta-analytic review of corridor effectiveness, Gilbert-Norton et al. 2010

> Habitat fragmentation, a frequent consequence of habitat loss, is a primary threat to populations and species because isolated subpopulations are expected to experience reduced population viability and ultimately greater risk of extinction. Colonization and

[5] A biotope is an area defined by particular environmental conditions (such as "littoral [coastal] muddy sand") that define the habitat of a particular biological community [Olenin & Ducratoy 2006].

> gene flow between habitat patches, however, can mitigate these effects [Gilbert-Norton 2010: 661].

This meta-analysis, consisting of 78 experiments from 35 studies, asked the question: Do ecological corridors increase movement between habitat patches, and how does that differ among taxa? The study's results answer the first part of the research question affirmatively: "There was approximately 50% more movement between habitat patches connected by a corridor than between isolated habitat patches" [Gilbert-Norton 2010: 665].

Furthermore, corridors increase movement for all taxa. "Most corridors are created for terrestrial vertebrates, including birds, although our data suggest that invertebrates and plants also benefit from corridors" [Gilbert-Norton 2010: 665]. This study found that corridors work equally well for all taxa except birds, for whom the corridors were used less; however, birds still favored corridors compared to surrounding matrix.

While three quarters of the experiments showed corridors to be more effective for movement compared to the matrix landscape, 23% of experiments showed corridors were less effective. The authors suggest several explanations for this result. It's possible that the "matrix habitat has been misclassified as nonhabitat for a study organism" [Gilbert-Norton 2010: 665], that the habitat quality of the corridor is not particularly high, or that the corridor is difficult to locate, given its small size compared to surrounding landscape. Furthermore, use of corridors varies by species.

> That almost a quarter of the studies showed organisms used matrix habitat rather than corridors to move between habitat patches furthers the idea that although corridors may be used by many species, they are unlikely to be used by all species, and whether corridors are relevant for land managers may depend on the species of interest [Gilbert-Norton 2010: 665].

The authors also observed that organisms showed greater use of natural corridors (those existing prior to the study) compared to those created and maintained for the study. The real-world applicability of this, as the authors note, is that "it may be better to protect natural landscape features that function as corridors rather than attempting to create corridors" [Gilbert-Norton 2010: 667]. This highlights the importance of protecting natural or semi-natural lands from development.

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Characterizing multispecies connectivity across a transfrontier conservation landscape, Brennan et al. 2020

Connectivity conservation pays attention to landscape connectivity to support animal species' movements, keep ecological processes intact, and promote biodiversity. While the strategy of conserving connected, non-fragmented areas and respecting animals' movement patterns is sound, in practice these plans are usually designed around a single species and its needs.

Brennan et al. looked at the limitations of a single-species focus, and evaluated the movement patterns of multiple species. They created connectivity maps for six large mammal species in the Kavango-Zambezi (KAZA) transfrontier conservation area straddling Angola, Zambia, Zimbabwe, Botswana, and Namibia, and assessed how each individual species' connectivity maps correlated with that of the others.

This then allowed the authors to identify good 'surrogate species for connectivity' – that is, species whose connectivity maps were good representations of other species' movements through the same area. They also took a look at different types of barriers to animal movements and determined that fences were the greatest obstacle to movement, while roads, rivers, and human-settled areas also deterred movement. Finally, they identified connectivity hotspots on the landscape, which are like bottlenecks through which multiple species pass due to barriers elsewhere. These connectivity hotspots are thus essential places to focus conservation efforts.

The researchers found the hyena and African wild dog to be the most apt surrogate species for connectivity, in spite of a popular practice of using elephants to determine the geographic targets of conservation efforts.

> In our examination of connectivity across the landscape, female elephants were found to be only weakly correlated with the five other species in our study. Spotted hyena and African wild dog, in contrast, were strongly correlated with the greatest number of species. They also appeared to be complementary surrogates (i.e. they were correlated with different species), in which case combining their connectivity models could further extend the relevancy of connectivity conservation plans to other species. Thus, as both species are also charismatic, wide-ranging species of conservation concern, they may represent good umbrella species for connectivity in the KAZA region [Brennan 2020: 1707].

They went on to say that "while elephants may not be good surrogate species for connectivity across entire landscapes, they may still be effective as a surrogate at local scales where they can help protect local movement pathways or stepping-stone habitats for other species" [Brennan 2020: 1707].

Their conclusion is not that we should stop paying attention to elephants, which serve important ecological functions and are an iconic and culturally significant animal. Rather, we should look for gaps that may arise if we only conserve areas based on elephant movements, and put these techniques of comparing and combining different species' movement patterns to use. Noting that animal movements and ecological dynamics play out at different scales, from entire landscapes and transnational parks to smaller corridors, they emphasized the importance of looking at connectivity for multiple species at multiple scales. They urged researchers and policy makers to take a more holistic multi-species approach to connectivity conservation.

Salvaging bycatch data for conservation: unexpected benefits of restored grasslands to amphibians in wetland buffer zones and ecological corridors, Mester et al. 2020

This study considers the effect of grassland restoration on amphibian populations in a 760-acre nature reserve – the Egyek-Pusztakócs Marsh System (EPMS) – established on former farmland in Hungary. The study shows that grassland restoration increased habitat range and quality for amphibians, extended hydrological supply, and limited genetic erosion among previously isolated populations. It also illustrates the role of smaller-scale ecological corridors.

> Grassland restoration … creates corridors that maintain connectivity among the amphibian (sub)populations in the EPMS but it may also increase the permeability of the landscape to establish and maintain connections to other nearby metapopulations. Grassland restoration can thus also have an effect of minimizing genetic erosion of populations induced by isolation, which is one of the major causes of global amphibian decline [Mester 2020: 7].
>
> Restoration can benefit amphibians by increasing the area of grasslands available for a variety of life activities such as foraging, burrowing, dispersal/ migration, or hiding from predators, aestivation and hibernation in the non-breeding period and by ensuring functional connectivity between wetlands both in the breeding and non-breeding periods [Mester 2020: 9].

Ecosystem service provision by road verges, Phillips et al. 2019

‘Road verges’ are strips of land on either side of roads and highways that are on average 3-4m wide, but can be as narrow as a few centimeters or many meters wide. “Road verges are commonly grassland habitats, but can be shrubland, forest or artificial arrangements of trees and horticultural plants, and we use the term also to include bare earth and freshwater bodies (e.g. ditches)” [Phillips 2019: 489]. They can also be barren ground or ditch. Not all road verges are managed; when management does occur, it is typically geared toward safety – clearing vegetation to enhance visibility.

There is currently an estimated 36 million linear kilometers of road network in the world, the length of which is expected to increase by 70% by 2050; thus, the total area of road verges will increase as well. “Road and road verge construction will displace habitats and cause many negative ecological and social impacts” [Phillips 2019: 494]. However, there is potential to mitigate that impact by maximizing the ecological value of road verges. Currently, “there may well be 270,000 km^2 of road verge globally (0.2% of land), which is similar to the total area of the United Kingdom” [Phillips 2019: 492], with this surface area expected to grow.

> While roads run like a network of veins across landscapes, causing widespread negative ecological impacts to adjacent areas, road verges form a parallel network and have the potential both partially to mitigate negative impacts of roads and to deliver environmental benefits [Phillips 2019: 490].

Where roads cut through natural habitat, the road verges will represent a net loss of biodiversity. By contrast, verges can increase biodiversity in highly degraded environments such as cities or industrial farmland. Furthermore, because of the growing urban population, the importance of natural and semi-natural environments will be increasingly important. Road verges designed to maximize ecological value thus have an important role to play in the health and wellbeing of urban residents.

> Road verges might increase connectivity in highly modified urban and agricultural landscapes if road verges of suitable size, habitat quality and continuity are created alongside roads, at least for species that are highly mobile or able to persist in narrow, linear habitats [Phillips 2019: 495].

While roads often act as barriers to wildlife and ecological connectivity, ecological corridor design could benefit by taking into account the potential benefits of road verges.

> If road verges were integrated into such [ecological corridor design] projects, they might play an important future role in increasing connectivity between natural and semi-natural habitats, particularly across otherwise habitat-poor, human-dominated landscapes where roads often occur [Phillips 2019: 495].

Road verges designed to maximize ecological value thus have an important role to play in the health and wellbeing of urban residents.

Fence ecology: frameworks for understanding the ecological effects of fences, McInturff et al. 2020

Conceptually the inverse of wildlife corridors, fences aim to disconnect. They are built to separate people across national borders, livestock from predators, to delineate property lines, and even to protect wildlife conservation reserves. Globally, fences are ubiquitous, more prevalent even than roads, and proliferating. Yet their ecological impact is relatively unstudied.

> Fences are often framed as a management tool rather than a globally significant ecological feature, and they are a notable omission from efforts to map global infrastructure, including the human footprint [McInturff 2020: 971].

This analysis reviews 446 studies starting from 1948 on various types of fencing to assess impacts; however, most of the studies focus on the effect of fencing on particular species (specifically, those the fencing is meant to protect), rather than on multiple species, communities or ecosystems.

> Conservation and restoration fences, for example, have support within the literature for their beneficial effects for wildlife and sensitive plant species for which they are built, making such species “winners” in the fencing game. On the other hand, there is a critical lack of information on species that are not the targets for which fences are built, and our review shows that only 10.8% (48 of 446) of studies focus on nontarget species [McInturff 2020: 975].

While fences aiming to protect particular species usually achieve that goal, they inevitably hurt other species.

> … often the clearest winners because of fencing are the species that humans value most, whereas losers are inevitable but may remain invisible [McInturff 2020: 975]. Broadly speaking, fences favor generalists and disturbance specialists, many of which are invasive, as well as small and small-ranged, nonmigratory species. Fences therefore heavily restrict what makes a species a winner [McInturff 2020: 975].

The deleterious effects of fences include: impeding migration, reducing gene flow between populations, restructuring community composition and obstructing interspecies interactions, such as between predators and prey. These community-level changes can have ripple effects in the ecosystem. For example, livestock fences effectively excluding dingoes in Australia led to this large predator’s eradication. “Without dingoes, researchers have tracked a continental-scale mesopredator [mid-level predator] release that has altered biodiversity and habitats over enormous areas of Australia” [McInturff 2020: 979].

While fences limit certain interspecies interactions, they concentrate others:

> Even where conservation or restoration fences seemingly protect whole habitats, research still points to differential outcomes for constituent species. In addition, pathogens and parasites may spread more rapidly where species interactions are concentrated within reserves. In central Kenya, for example, smaller fenced reserves produced higher gastrointestinal parasite infection rates among impala [McInturff 2020: 977].

The authors recommend a greater research focus on the cumulative ecological effects of fencing, policy that limits fence building and encourages fence removal or fence design that is more wildlife-friendly. They caution that fencing is among the major drivers of anthropogenic change.

> As fencing continues to rapidly proliferate, there is potential for a dangerous future in which fences simultaneously alter ecological processes at multiple scales, likely producing more losers than winners, and potentially resulting in ecosystem state shift or collapse [McInturff 2020: 977].

Livestock fences effectively excluding dingoes in Australia led to this large predator's eradication. "Without dingoes, researchers have tracked a continental-scale mesopredator [a mid-level predator] release that has altered biodiversity and habitats over enormous areas of Australia" [McInturff 2020: 979].

European Context

Status of the Natura 2000 network (from State of Nature in the EU report), EEA (European Environmental Agency) 2020

While not an ecological corridor per se, the Natura 2000 network is the largest coordinated network of conservation areas in the world. Covering 17.9% of Europe's land area and nearly 10% of the continent's marine areas, the network includes 27,852 sites with an area of 1,358,125 km^2. The terrestrial portion of the Natura 2000 network is mostly covered by forests and transitional shrublands. It also includes grasslands and wetlands, as well as pastures, cropland and a small amount of artificial surface (developed/built land).

> Member States need to ensure that sufficient protection and appropriate measures are implemented in Natura 2000 sites for habitats and species of community interest and that they form a functional network [EEA 2020: 109].

However, the sites are not strictly protected by virtue of being part of the network. In fact, the sites include a variety of land uses.

> Within the network, arable land and permanent crops have increased, while grasslands and forests have decreased. … Pastures and mosaic farmland (with approximately 18 %) and inland wetlands and water bodies (with approximately 10 %) have been extensively transformed into arable land and permanent crops both inside and outside the network. Recent research has shown, however, that high nature value (HNV) farmland inside Natura 2000 sites is less likely to be converted into artificial surfaces than such farmland outside the network and is more likely to maintain its pattern of mosaic farming [EEA 2020: 113].

This assessment of the network's effectiveness found that "species and habitats are more likely to have a good conservation status if they are well covered by the Natura 2000 network" [EEA 2020: 121]. However, limited monitoring inside and outside the network prevents a more detailed analysis of Natura 2000's effectiveness. Furthermore, due to a limited implementation of conservation measures, the network's potential has not yet been fully "unlocked," according to the report.

To improve Natura 2000's potential, the authors recommend, among other measures, improving connectivity between protected areas. Noting that sites chosen for inclusion in the network are often motivated by economic rather than ecological interests.

> Incoherent planning and site selection approaches between and within Member States has led to insufficient functional connectivity and spatial connectedness between neighboring countries and habitats and gaps in coherence within Member States. This highlights the need to increase connections between protected areas and the level of protection beyond the site [EEA 2020: 122].

Also recommended is increasing stakeholder participation, such as through citizen science monitoring initiatives, and better integration of biodiversity protections into other policy domains.

> The resulting low awareness of the diverse benefits produced by the Natura 2000 network is often compounded by a long-standing conflict between economic or political interests and conservation goals. There is thus an urgent need to increase coherence between biodiversity policy and other policy areas, such as in the fields of agriculture and economic and rural development, and create a more integrated approach to address

> potential conflicts and trade-offs between various interests while fostering synergies [EEA 2020: 124].

The report's summary conclusion recommends increasing marine and terrestrial conservation areas in the Natura 2000 network to 30% each, strictly protecting these areas, and improving connectivity among them.

Blue and green corridors [*Les trames vertes et bleues*] in France, Ministry of Ecological Transition 2017

Spurred to action by the European Union and a vision for a pan-European ecological network, France encoded the idea of the "trames vertes et bleues" into law in 2009. The national government worked with all the regional governments to develop maps showing areas with the highest levels of biodiversity. This includes protected areas, stretches of coastline, riparian zones, woods, and other undeveloped areas, whether public or private. The maps also show ecological corridors – both those in good condition needing to be preserved, and those that are highly degraded and requiring restoration.

The regional maps are meant to be integrated into urban planning at the level of city and county (department). Rather than being a regulatory tool, the maps are an information source allowing urban development to proceed in a way that limits impact on biodiversity. The ecological corridor initiative is designed as an invitation and encouragement to local governments, organizations, businesses and individuals to collaborate and to act in favor of biodiversity.

> The preservation and restoration of ecosystem connectivity entails acting everywhere possible: in rural environments, in aquatic ecosystems and in urban areas [MTES 2017, translation].

Articulating the politics of green and blue infrastructure and the mitigation hierarchy for effective biodiversity preservation in France [*Articuler la politique Trame verte et bleue et la séquence Éviter-réduire-compenser: complémentarités et limites pour une préservation efficace de la biodiversité en France*], Chaurand & Bigard 2019

This article reviews the historical development of two pieces of environmental legislation in France - the use of the "mitigation hierarchy" to assess and limit environmental impact in project development and the promotion of ecological corridors. Theoretically, these two laws overlap when urban development projects in proximity to areas of ecological significance use the mitigation hierarchy (avoid, reduce, compensate) to ensure these zones are protected within the scope of the project.

- 1976: “Protection of Nature” law in France introduced the mitigation hierarchy, aiming to avoid or reduce harm to the environment, or to compensate if harm is unavoidable.
- 1992: Concept of “biodiversity” entered public discourse internationally, following the Earth Summit in Rio, Brazil.
- 1996: France ratified European ecological corridor strategy.
- 1999-2000: Concept of “sustainable development” emerged in France.
- 2004: National strategy for protecting biodiversity adopted.
- 2007: “Grenelle de l’Environnement” meeting created the “Trame Verte et Bleue” (TVB) policy (green and blue infrastructure, encompassing ecological corridors)
- 2016: Biodiversity law enacted, creating national agency and regional committees on biodiversity

In spite of this policy evolution, commitment to ecological corridors has yet to move from a “TVB papier” to a “TVB de projets et d’action.” In other words, much discussion and mapping efforts have not yet resulted in the development of the imagined ecological corridor network. The authors speculate as to why this is so, explaining that the resources and coordination needed for enforcement are lacking. Even though “the creation, preservation and restoration of ecological connectivity” has been integrated into urban planning code, such considerations are often sidelined. Furthermore, definitions are vague: the objective of the TVB is the “good condition” of ecological continuity, but “good condition” is not defined. Lastly, taking action in defense of ecological continuity requires pro-active collaboration among levels of government from local to regional to national.

The authors propose better integration of these to policy tools. For example, the TVB designates certain non-protected areas throughout the country that are ecologically functional and serve a role in the eco-corridor network as key areas to “preserve.” With better communication between this TVB framework, the mitigation hierarchy could be applied at the level of “avoiding” harm to places designated as preservation priorities, but lacking formal “protected” status. In projects where harm is unavoidable, the mitigation hierarchy could be applied at the level of “reducing” harm to maximize the percentage of remaining green space as well as the permeability to wildlife of the built structures (such as passageways through fences). The “compensation” level of the mitigation hierarchy could be applied in the context of regenerating ecosystem function to areas designated in the TVB schema as needing ecosystem restoration.

The authors note that advocates for the TVB are clustered at the national level and within research institutions, while the people responsible for urban planning decisions are local and are not necessarily well versed in the scientific framework for the TVB. Local actors tend to focus on priorities other than ecological continuity. One measure to address this, according to

the authors, would be the training of local “relays” to transmit knowledge of ecological principles vis a vis the TVB to local urban planners.

Woods and hedgerows of Brittany countryside [*Le bocage Bretagne*], OEB (L’Observatoire de l’Environnement en Bretagne) 2018

Produced by a regional consortium on the environment in Brittany, France, this report describes the ecological value of woody strips encircling agricultural fields and enmeshing the countryside, their decline, and ways to incentivize their protection.

Brittany is a heavily agricultural region that also features a long stretch of coastline where urban development and expansion is ongoing. Due to mechanization and enlargement of farm fields, average parcel size has increased since the 1950s, shrinking the extent of woody hedgerow (“bocage”) between fields. Between 1996 and 2008, the total length of hedgerow decreased 12%. This change is concerning because Brittany is already one of the most fragmented and least wooded parts of France.

The report explains the value of the bocage is its provisioning of habitat, connectivity between habitats, biodiversity, erosion control, groundwater recharge, and flood mitigation. Half the population of Brittany lives in areas susceptible to flooding. Furthermore, at least five endangered animal species depend on the habitat created by the bocage. Protection of this woody network is key to remedying both problems, while also providing direct benefits to farmers, such as habitat for pest predators.

The form and shape of the bocage varies throughout the region, but can include grasses, bushes and/or trees, forming one or more layers of vegetation; and heterogenous landscape features such as berms, ditches, logs, and rocks/boulders, which create microhabitats.

> The network of hedge and berms, accompanied by fields, ponds and wetlands, constitutes an important natural environment because of its heterogeneity and potential for complex exchanges. It has the particularity of being able to reach a myriad of increasingly isolated natural spaces in the heart of a changing agricultural countryside subject to ongoing urbanization. Similar to a forest edge environment, the richness of the bocage can be explained by the diversity of habitats it adjoins [OEB 2018: 8, translated].

Regulatory and incentive programs payments have sought to encourage farmers to preserve their hedgerows. However, the authors suggest that a stronger economic valuation of these linear woods is needed to protect and expand them. They suggest strategies for stimulating the market for firewood and other products harvested from sustainably managed hedgerow, where biodiversity protection is an explicit aim and co-benefit.

Americas Context

Shaping land use change (LUC) and ecosystem restoration in a water-stressed agricultural landscape to achieve multiple benefits, Bryant et al. 2020

In spite of its obvious benefits, agriculture, which covers one third of the Earth's land surface, damages biodiversity and ecosystem services. In some regions, land degradation and depletion of water resources from irrigation have been so great that historical levels of food production in these regions risk decline. Some areas of previously productive farmland will likely need to be retired from use. Within this context, maintaining and enhancing natural corridors and promoting semi-natural, multifunctional landscapes can significantly contribute to recovering biodiversity and mitigating air and water pollution.

Using California's San Joaquin Valley (SJV) as a case study, this paper illustrates a pragmatic approach to incorporating ecological corridors into working landscapes. The authors offer a new analytical approach that simultaneously incorporates resource-constrained (water, in this case) land-use change (LUC) modeling within the planning and optimization process. The goals are to simultaneously:

- Meet water-use-reduction policy goals for the area under study within the next two decades
- Identify lands for retirement that are (1) likely to be retired anyways and (2) offer high-value habitat for native species and biodiversity.

Over the past century, SJV has been transformed into one of the largest agricultural economies in the world. However, this economic success has been costly to the SJV in several ways, including:

- Damaged infrastructure: high rates of groundwater extraction in the SJV have led to groundwater overdraft and unreplenished aquifers, resulting in large-scale land subsidence. Most of the subbasins in the SJV are categorized as critically overdrawn, and some regions have sunk over 8 meters since the early 20th century; this land subsidence further imperils water availability and quality by impacting water storage and delivery infrastructure.
- Decreased human health, as a result of impaired air and water quality, leading to chronic health problems

- Threats to wildlife and biodiversity; for example, some species have lost up to 98% of their habitat range, and over 35 native species are listed as threatened or endangered

“In response to these challenges, and amid significant drought-driven fallowing, California passed the Sustainable Groundwater Management Act (SGMA), which … obligates locally governed groundwater subbasins to develop plans that will achieve sustainable groundwater use over the next two decades” [Bryant 2020: 2]. To meet these requirements, many subbasins will meet with severe groundwater pumping restrictions. If these areas are not able to coordinate their pumping activities and augment water supplies, the SGMA may require a reduction in cultivation area through fallowing or permanent retirement.

Given the likely retirement of 86,000 ha of irrigated agricultural land, the authors explore spatial optimization of retired land for conservation efforts. They find that a key strategy is the identification of areas that were destined for retirement from cropping which could be shifted to restoration and habitat enhancement, as well as possibly shifting some areas destined for retirement that have “low habitat value” with regards to wildlife for areas with “high habitat value.” Priority restoration areas identified in this analysis include many that are contiguous and located near designated wildlife areas.

Importantly, the analysis presented here is “explicitly organized to help inform engagement between conservation actors and agricultural land managers about how habitat goals can be achieved in ways that benefit communities in the SJV” [Bryant 2020: 3]. The potential positive futures indicated by such analysis can be used to identify opportunities for collaboration between the conservation and agricultural communities, with a goal of guiding land use change toward achieving multiple benefits, such as recovery of imperiled natural communities, resilient agricultural production, and improved public health outcomes.

> While it poses a great challenge, the impending transformation in the SJV also presents an opportunity to proactively shape the landscape in ways that not only ensure agricultural and water sustainability, but also achieve many other socio-ecological goals, such as biodiversity protection and improved human health. However, given that achievement of many of these objectives is determined by **where** things happen on the landscape (rather than simply the aggregate amounts of cultivation, retirement, or restoration), stakeholders need a systematic way to integrate these objectives to inform multi-benefit spatial planning [Bryant 2020: 4].

Integrating Agricultural Landscapes with Biodiversity Conservation in the Mesoamerican Hotspot, Harvey et al. 2007

> The fate of biodiversity within protected areas is therefore inextricably linked to the broader landscape context, including how the surrounding agricultural matrix is designed and managed [Harvey 2007: 8].

Rather than discussing ecological corridors per se, this article emphasizes the importance of a whole-landscape approach to biodiversity conservation. Pointing out that protected nature reserves are weakened when isolated, these authors focus on the role of the entire surrounding agricultural matrix for restoring connectivity.

> In contrast to the prevailing trend of managing protected areas and productive lands separately, we propose integrated landscape management in which conservation and production units within the agricultural matrix are managed jointly for long-term sustainability. We do not advocate agricultural intensification to spare further forest conversion because this approach is unlikely to have the intended outcome, for reasons discussed. Instead, conservation efforts should be based on the recognition that how agriculture is conducted and how different land uses are distributed spatially and temporally determine the region's biodiversity. Lasting conservation will therefore require alliances among conservation biologists, farmers, and land managers to actively plan the future of Mesoamerican landscapes [Harvey 2007: 9].

The sections of the agricultural matrix the authors prioritize for biodiversity conservation include areas near riparian and other key ecological corridors, and they recommend leveraging support for the Mesoamerican Biological Corridor to spur regional action. Priority conservation areas are also more likely to encompass landscapes with a high diversity of indigenous and traditional cropping systems than those dedicated to industrial agriculture because "the chances of reconciling farming and biodiversity conservation there [agro-industrial systems] are slim" [Harvey 2007: 10].

The authors argue that, in contrast to large-scale, export-oriented industrial production, small-holder and indigenous agricultural systems are more compatible with biodiversity conservation, increased food production and rural income. The authors propose economic and regulatory instruments and greater regional collaboration to enhance native tree cover on farms, promote traditional, ecologically based farming practices, and to protect remaining intact habitat and restore degraded lands. The overarching vision is to accomplish conservation and agricultural production objectives for the region in mutually reinforcing ways.

> The fate of biodiversity within protected areas is therefore inextricably linked to the broader landscape context, including how the surrounding agricultural matrix is designed and managed [Harvey 2007: 8].

The concept of green corridor and sustainable development in Costa Rica, Beauvais & Matagne 1999

The concept of sustainable development presumes that human economic systems and overall wellbeing depend on functioning ecosystems. Therefore, ecological rhythms should not be transgressed to the point that they fail to provide the vital services needed today and in future generations.

> According to this model, economic development becomes a necessary but insufficient condition for society to progress [Beauvais & Matagne 1999: 6, translated].

Costa Rica holds at least 5% of the world's species, in spite of making up 0.03% of its land surface. As an isthmus, Costa Rica is influenced by weather patterns from two oceans, as well as a north-south migration route. In addition to this, its mountainous terrain creates a heterogenous mosaic of habitats and niches. However, the country has been severely deforested. Forest covered 66% of land surface in 1940, and only 25% by 1987; the loss of forest led to extreme erosion.

As presented in this article, an ecological corridor consists of at least two protected ecosystem patches that are connected by a protected vegetated strip of at least a few kilometers in width, and the whole area surrounded by a buffer zone. Multiple units of two connected patches could in turn be connected, stretching into a corridor that the whole length of the country. A green Costa Rican corridor could connect to green corridors in adjacent countries, ultimately recreating the entire isthmic corridor that once existed.

However, the tone of this article is not optimistic about conservation, citing several political obstacles to conservation and ecosystem restoration. According to the authors, a combination of neocolonialist pressure, poverty, corruption, and capitalistic interests allow for trees to be cut even in protected areas and prevent the establishment of new protected areas and corridors.

The Mesoamerican Biological Corridor in Panama and Costa Rica, Dettman 2006

At the end of the 1980s, as a period of severe conflict in Central America was winding down, most countries in the isthmus signed the Charter Agreement for the Protection of the Environment, which established a sustainable development commission. At the same time, the "Central American Protected Areas System (SICAP) created approximately 11.5 million hectares of protected areas throughout the region" [Dettman 2006: 18].

This paved the way for international attention and investment in what became the Mesoamerican Biological Corridor (MBC). The original intention was to promote biodiversity and economic development in tandem through investment in local projects. However, in the 2000s, the international coordinators of the MBC shifted the focus from biodiversity protection (although the establishment of ecological corridors remains an objective) to a greater emphasis on economic development. This author explains that the institution's decision-making process is overly top-down, and would benefit from input from local people who are implementing projects on the ground.

Between Bolivar and Bureaucracy: The Mesoamerican Biological Corridor, Liza Grandia 2007

Written by an anthropologist working in Central American conservation efforts for more than 10 years, this article describes the Mesoamerican Biological Corridor (MBC) project as having succumbed to a neoliberal agenda. Although originally spearheaded by Central American environmentalists, the notion of cross-border environmental collaboration was adopted by the World Bank and large international conservation organizations working in Central America in the 1990s. In the hands of these international giants, the biological corridor initiative became a bureaucratic, top-down project, deaf to the voices of local communities.

> With all this new bureaucracy, a broad and unfocused agenda, and the challenges of high-level political coordination, the MBC quickly lost its potential to inject a stronger environmental justice component into regional biodiversity conservation programs. Indeed, the MBC that emerged from the World Bank's incubator was decidedly more business-oriented than initial proposals for Central American environmental coordination at the 1992 Earth Summit [Grandia 2007: 486].

In this context, the MBC's conservation efforts have focused more on securing land for protected parks and less on community-based initiatives. The author suggests that in addition to land protection, the MBC should engage farmers in capacity building for eco-agriculture with a view toward achieving landscape-wide ecological connectivity.

> The corridor approach might also draw greater attention to the agrarian contexts outside of parks, which may be just as ecologically important as what happens inside parks. By bringing agricultural systems into conservation debates, corridors may present new opportunities for supporting fair-trade projects and other small-scale agroforestry systems compatible with conservation. In other words, corridors could offer a method for moving beyond protectionism to embrace a mosaic vision for conservation that includes local people more explicitly. Corridor planning frameworks also could provide more democratic conservation forums [Grandia 2007: 484].

Effectiveness of Panama as an intercontinental land bridge for large mammals, Meyer et al. 2019

> One of the world's largest corridor projects is the Mesoamerican Biological Corridor (MBC). Initiated in the 1990s, the MBC aims to connect protected areas between southeastern Mexico and Panama [Meyer 2019: 2].

The ecological functionality of the MBC has not been much assessed, in part because direct approaches to measuring connectivity are costly and challenging. In this study, researchers used a simpler, indirect approach to measure forest connectivity through Panama for nine mammals. Using camera traps (cameras that are automatically triggered by a change in some activity in the vicinity, like the presence of an animal), they documented the presence (or absence) of these mammals in 28 forest sites along the Atlantic coast. The corridor was presumed to be functioning for animals whose presence was established across the entire length of the monitored range.

The species monitored in this study are forest specialists, including ungulates, carnivores and an insectivore, all of which are threatened by habitat loss and hunting, some more than others. Of the 43% of land in Panama that is forested, 44% is protected, mostly along the Atlantic coast. Steady economic development threatens remaining ecosystems with investments in large infrastructure projects, real estate, mining, tourism, and energy.
Large mammals are an indicator species for the success of conservation efforts. This is because:

> Large mammals are generally at a higher risk of extinction in disturbed landscapes than other taxa because their large home ranges and low population densities at broad spatial scales mean their populations are more likely to be fragmented and because they are heavily hunted [Meyer 2019: 3].

The researchers found that even the four most prevalent species in the study are susceptible to population fragmentation by any further habitat loss.

> We found that there was little connectivity for white-lipped peccary [a pig-like animal] and white-tailed deer and that, although 4 of the species (collared peccary, red brocket deer, puma, and ocelot [a wild cat]) occurred in most of the sites, a small decrease in connectivity of 20% would disrupt their continuous distributions across Panama. White-lipped peccary, giant anteater, white-tailed deer, jaguar, and tapir [a pig-like animal with a short trunk] had lower probability of occurring in all the sites and were therefore even more at risk of connectivity loss, as evidenced by >1 connectivity gap. This indicates the MBC may not function for the majority of species, especially considering we did not account for potential effects of hunting, which would make connectivity even more challenging [Meyer 2019: 8].

Citing imminent development projects, such as a new road that will pass through the forested northern coast and associated large hotel projects, the authors predict that ongoing loss of connectivity is likely. Moreover, the deteriorating condition of the corridor in Panama bodes poorly for the MBC overall.

> The disruption of connectivity between tropical forests in Central America, and hence the possible separation of mammal populations, is an indicator of the overall functioning of the MBC for wildlife [Meyer 2019: 11].

Belize creates one of Central America’s largest biological corridors, Dasgupta 2018

The Belize government approved a plan in February 2018 to create a 110-square-kilometer biological corridor connecting two nature reserves in the northeast of the country. This outcome resulted from collaboration among NGOs, the government and private property owners. The latter agreed to conserve (to not deforest or otherwise degrade) the parts of their land that would become part of the wildlife corridor. In exchange, the government would not collect taxes on this land. This corridor, which was initiated in the context of the larger Mesoamerican Biological Corridor project, is meant to protect jaguars, cougars and tapirs, among other wildlife.

The woman building the forest corridors saving Brazil’s black lion tamarin, Zanon 2020

“The tamarin is unable to do anything to save its own species. And we, human beings, are the ones who are destroying their environment,” says conservationist Gabriela Rezende. “So, when I got the opportunity to see this animal in the wild, I felt partly responsible for its future.”

Rezende works with the Institute for Ecological Research in the Brazilian state of Sao Paolo to create ecological corridors connecting the forest fragments where the world’s only 1,800 black lion tamarin live in isolated populations. Since 1984, the institute has worked to protect this small primate species, which had reached a low point of 100 individuals and was listed as “critically endangered.” In addition to research and forest restoration, the institute also does environmental education with the local communities. This includes collaboration on nine tree nurseries administered by local people as small businesses that also provide school kids the chance to learn about local forest species that will be planted in corridors.

Leveraging a state policy requiring 20% of privately owned property to be in nature reserves, Rezende worked with landowners to identify patches to be restored that would physically connect forest fragments. Once corridors are complete, the total amount of land in connected habitat will be 111,000 acres. Rezende estimates the black lion tamarin population could increase 30% once it’s able to use the whole forest corridor. The restoration project will benefit other species too, including anteaters, tapirs (a pig-like animal with a short trunk), pumas, and ocelots (another wild cat species).

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