Summary of the Science and Policy Surrounding Mycorrhizal Fungi

I. General Mycorrhizal Scientific Background

Study after study has revealed that soil biota, particularly fungi that form symbioses with plant roots (mycorrhizae), provide a suite of ecosystem services that support the integrity and resiliency of natural and human communities (Markovchick et al. 2023), especially forests. Mycorrhizae are known to reduce erosion and nutrient loss (e.g. Burri et al. 2013; Mardhiah et al. 2016), increase plant water use efficiency and water retention and cooling capacity in the landscape (Querejeta et al. 2006; Gehring et al. 2017; Wu & Xia 2005), store carbon in the ground (e.g. Orwin et al. 2011; Nautiyal et al. 2019), help plants adapt changes in climate (Gehring et al. 2017; Patterson et al. 2019), and resist pests and pathogens (Reddy et al. 2006; Rinaudo et al. 2010).

Many reports suggest that beneficial native fungi, including native mycorrhizae are rare and frequently in decline. The Survey and Manage Standards and Guidelines of the Northwest Forest Plan found that 55% of the 234 fungal taxa in the program were found at fewer than 20 locations, and 42% were found at 10 or fewer sites (Molina 2008). For comparison, the Eastern prairie fringed orchid (*Platanthera leucophaea*) is extant in 59 populations and listed as threatened (USFWS 2019), while its relative, the chaparral rein orchid (*Platanthera cooperi*) is found at 162 locations and is considered vulnerable (The Calflora Database 2022).

The decline of mycorrhizal fungi can be more difficult to assess because this category includes fungi that do not form large fruiting bodies above ground, such as with Arbuscular mycorrhizal fungi (AMF). However, many studies report declines in mycorrhizal fungi due to various causes including land use change, invasive species, pollution deposition, and herbicide use (e.g. Meinhardt & Gehring 2012; Swaty et al. 2016; Lilleskov et al. 2019). Climate change also appears to be threatening the type of mycorrhizal fungi known to best support carbon sequestration called ectomycorrhizal fungi (EMF)(Baird & Pope 2021).

In some cases, the dangers facing beneficial fungi mirror those for other species, and the same conservation strategies could benefit fungi (Minter 2011). For example, Clemmensen et al. (2013) found that habitat fragmentation, a common threat to biodiversity, is also a concern for mycorrhizal fungi and conservation mycology. Thus, conservation programs targeting the mitigation of fragmentation could benefit both charismatic taxa and lesser known taxa like mycorrhizal fungi. However, Cameron et al. (2019) documented geographic mismatches between terrestrial aboveground and soil (including mycorrhizal) biodiversity, finding that these mismatches cover 27% of the earth's terrestrial surface. Thus, efforts to protect areas of aboveground biodiversity may not sufficiently reduce threats to soil biodiversity (Cameron et al. 2019).

Even within areas that are protected, disturbances such as logging and thinning (Wiensczyk et al. 2002), the treatment of invasive vegetation with pesticide (Helander et al. 2018), or self-reinforcing soil legacies left after invasion by exotic vegetation (e.g. Meinhardt & Gehring 2012), may quietly continue to reduce beneficial fungi, if these impacts are not recognized and specifically addressed as part of land management planning (Davoodian 2015; May et al. 2018; Willis 2018; Markovchick et al. 2023). These effects are not short-term, and ripple throughout the ecosystem, as evidenced by study after study that shows the need for and effectiveness of restoring diverse native mycorrhizal communities after various kinds of disturbance. For example, Pankova et al. (2018) found that a single fungicide application left mycorrhizal inoculum and plant outcomes far from reference levels even after five years.

While much of the science demonstrating the importance of mycorrhizal interactions is recent, the concepts are not new. For example, the Forest Service's own scientists (Harvey et al., 1994) invoked the relationship between chemical properties and biological properties: "Productivity of forest and rangeland soils is based on a combination of diverse physical, chemical and biological properties." In addition, due to its biodiversity, soil, far from being an inert, non-biological substrate, has been called the "poor man's tropical rainforest" (Giller 1996). The soil microbial world is known to be a foundational driver determining the habitat type, health, resiliency, and ecosystem services of natural areas (e.g. Singh & Gupta 2018; Cameron 2010; Wubs et al. 2016; Peay et al. 2016). Over 1,000 scientists and 70 institutions have urged agencies to recognize the broad relevance of the microbial world to sustaining healthy ecosystems and life on earth, and protect and harness this utility in responding to climate change (Cavicchioli et al. 2019). Yet, the USFS continues to ignore microbial communities when considering the tools available to support and enhance forest resilience, and when considering the impacts of their actions.

II. Mycorrhizal Ecosystem Services

A. Forest Service Ecosystem Services Policy & Direction

In 2005, the United Nations issued a report titled, "The Millennium Ecosystem Assessment" that significantly advanced the concepts and definitions of ecosystem services. The report identified four main categories:

- Provisioning Services such as food, clean water, fuel, timber, and other goods;
- Regulating Services such as climate, water, and disease regulation as well as pollination;
- Supporting Services such as soil formation and nutrient cycling; and
- Cultural Services such as educational, aesthetic, and cultural heritage values, recreation, and tourism.

Importantly, the Forest Service adopted these categories and definitions in its 2012 National Forest System Land Management Planning Rule

- (a) Integrated resource management for multiple use. The plan must include plan components, including standards or guidelines, for integrated resource management to provide for ecosystem services and multiple uses in the plan area.

- …Ecosystem services. Benefits people obtain from ecosystems, including:
    - Provisioning services, such as clean air and fresh water, energy, fuel, for- age, fiber, and minerals;
    - Regulating services, such as long term storage of carbon; climate regulation; water filtration, purification, and storage; soil stabilization; flood control; and disease regulation;
    - Supporting services, such as pollination, seed dispersal, soil formation, and nutrient cycling; and
    - Cultural services, such as educational, aesthetic, spiritual and cultural heritage values, recreational experiences, and tourism opportunities.

(36 C.F.R. § 219.10, § 219.19)

When defining soil function, the Forest Service internal directives provides the following:

- Soil biology. The presence of roots, fungi, and micro-organisms in the upper sections of the soil.
- Soil hydrology. The ability of the soil to absorb, store, and transmit water, both vertically and horizontally.
- Nutrient cycling. Soil stores, moderates the release of, and cycles nutrients and other elements.
- Carbon storage. The ability of the soil to store carbon.
- Soil stability and support. Soil has a porous structure to allow passage of air and water, withstand erosive forces, and provide a medium for plant roots. Soils also provide anchoring support for human structures and protect archeological treasures.
- Filtering and buffering. Soil acts as a filter to protect the quality of water, air, and other resources. Toxic compounds or excess nutrients can be degraded or otherwise made unavailable to plants and animals.

Forest Service Manual 2550.5 at 8-9. As detailed in the following section, ecosystem services provided by mycorrhizal fungi directly relate to those identified by the Forest Service as important soil functions, and the significant benefits provided by mycorrhizal fungi must be considered in detailed environmental analysis.

B. Scientific Background on Mycorrhizal Ecosystem Services

Ecosystem services are defined as ecological functions and processes that contribute to human wellbeing (Costanza et al. 1997). Available data highlight the many and meaningful contributions of mycorrhizae to ecosystem services and integrity, ranging from drought resilience to pest control to climate stabilization (e.g. Christensen, 1989; Peay et al. 2016).

In the following sections, we include the definitions for each category from Costanza et al. (1997) and briefly review the fungal contributions. In Table 1, we highlight many of these studies and provide examples of some of the magnitudes of effects seen due to mycorrhizae (see effect sizes and percent changes).

Table 1: Some examples of mycorrhizal ecosystem services and effects sizes.

Ecosystem Service Category	Study	Effect Type	% Change[2]	Effect Size[3]
Climate	Clemmensen et al. 2013	carbon storage	50-70%	
Climate	Orwin et al. 2011	carbon storage	14%	
Climate	Nautiyal et al. 2019	carbon storage	82%	
Disturbance regulation	Auge et al. 2015	drought adaptation	111%	0.75
Disturbance regulation	Auge et al. 2015	drought adaptation	49%	0.4
Disturbance regulation	Auge et al. 2015	drought adaptation	24%	0.2
Disturbance regulation	Miozzi et al. 2020	reduction in disease severity	200%	
Disturbance regulation	Ruiz-Lozano & Azcón 1995	support plant growth	938%	2.34
Disturbance regulation	Ruiz-Lozano & Azcón 1995	support plant growth	3542%	3.60
Disturbance regulation	Stella et al. 2017	remove soil toxins	19%	
Disturbance regulation	Stella et al. 2017	remove soil toxins	41%	
Disturbance regulation	Stella et al. 2017	remove soil toxins	51%	
Disturbance regulation	Wulandari et al. 2016	increase plant health & growth at toxic site	125%	0.81
Disturbance regulation	Wulandari et al. 2016	increase plant health & growth at toxic site	200%	1.10
Disturbance regulation (Restoration)	Koziol & Bever 2017	support plant survival	40%	
Disturbance regulation (Restoration)	Koziol & Bever 2017	support plant growt/health	300%	
Disturbance regulation (Restoration)	Koziol & Bever 2017	increased leaves/tillers	200%	
Disturbance regulation (Restoration)	Koziol & Bever 2017	increased species richness	55%	
Disturbance regulation (Restoration)	Koziol & Bever 2027	increased species diversity	70%%	
Disturbance regulation (Restoration)	Maltz & Treseder 2015	support plant growt/health		0.63
Disturbance regulation (Restoration)	Neuenkamp et al. 2019	boost species richness	30%%	
Disturbance regulation (Restoration)	Neuenkamp et al. 2020	boost restoration plant growth		1.70

Ecosystem Service Category	Study	Effect Type	% Change^2	Effect Size^3
Disturbance regulation (Restoration)	Rua et al. 2016	support plant growt/health		0.25 to 1.25
Disturbance regulation, Pollination	Botham et al. 2009	support plant growt/health	30%	
Disturbance regulation, Pollination	Botham et al. 2009	support plant growt/health	23%	
Disturbance regulation, Water	Egerton-Warburton et al. 2008	support water uptake/movement	up to 7 µmol/m/hr	
Disturbance regulation, Water	Egerton-Warburton et al. 2008	support water uptake/movement	up to 6.5 µmol/m/hr	
Disturbance regulation, Water	Querejeta et al. 2006	drought adaptation	111%	0.75
Erosion control	Burri et al 2013	reduce erosion & increase soil stability	74%	0.94
Erosion control	Graf and Frei 2013	reduce erosion & increase soil stability	533%	1.85
Erosion control	Mardhiah et al 2016	reduce erosion & increase soil stability	16%	
Erosion control	Rillig et al 2010	reduce erosion & increase soil stability	116%	0.77
Erosion control	Rillig et al 2010	reduce erosion & increase soil stability	18%	0.17
Erosion control	Zheng et al 2014	reduce erosion & increase soil stability	267%	1.30
Erosion control	Zheng et al 2014	reduce erosion & increase soil stability	13%	0.12
Erosion control, Water	Andrade et al 1998	reduce erosion & increase soil stability	14%	0.13
Genetic resources	Ina et al. 2013	medical contributions by EMF	54%	0.43
Genetic resources	Ina et al. 2013	medical contributions by EMF	39%	0.33
Genetic resources	Ina et al. 2013	medical contributions by EMF	10%	
Genetic resources	Zeng et al. 2013	medical contributions by AMF	84-270%	
Habitat & biodiversity	Stevens et al. 2018	ecosystem abundance/diversity from AMF-contributed phosphorus	48%	
Habitat & biodiversity	Tracy & Markovchick 2020	habitat suitability for endangered bird	1.2 hectares	
Habitat & biodiversity	van der Heijden et al. 2015	land plants that rely on native mycorrhizae	86%	
Nutrient cycling	Bonneville et al. 2009	mineral weathering & supply	50-75%	1.61
Nutrient cycling	Quirk et al. 2015	mineral weathering & supply	400%	1.61
Nutrient cycling	Taylor et al. 2012	mineral weathering & supply	100%	0.69
Pest regulation	Abdalla & Abdel-Fattah 2000	pathogen reduction by AMF	80%	
Pest regulation	Babikova et al. 2013	residence time of pest controls	333%	
Pest regulation	Babikova et al. 2013	residence time of pests	186%	
Pest regulation	Karst et al. 2015	tree growth after pests	700%	2.08
Pest regulation	Karst et al. 2015	monoterpene production	500%	1.79
Pest regulation	Reddy et al. 2006	AMF reduction of pathogen	70%	-1.20
Pest regulation	Reddy et al. 2006	AMF reduction of pathogen	75%	-1.39
Pest regulation	Rinaudo et al. 2010	AMF reduction of invasive vegetation	45%	-0.60

Ecosystem Service Category	Study	Effect Type	% Change[2]	Effect Size[3]
Pest regulation	Rinaudo et al. 2010	AMF reduction of invasive vegetation	25%	-0.29
Pest regulation	Waller et al. 2016	AMF reduction of invasive vegetation	29%	-0.34
Pollination	Aguilar-Chama and Guevara 2012	flower mass	100%	0.69
Pollination	Cahill et al. 2008	pollinator visitation rates	193%	1.08
Pollination	Cahill et al. 2008	type of pollinators	shifted pollinator species	
Pollination	Gange and Smith 2005	flower number	63%	0.49
Pollination	Gange and Smith 2005	flower nectar sugar content	55%	0.44
Pollination	Gange and Smith 2005	pollinator visitation rates	33%	0.29
Pollination	Gange and Smith 2005	pollinator visitation rates	200%	1.10
Pollination	Gange and Smith 2005	pollinator visitation rates	100%	0.69
Pollination	Gange and Smith 2005	nectar production	50%	0.41
Pollination	Gange and Smith 2005	nectar production	81%	0.60
Pollination	Lu and Koide 1994	days to flowering	23%	0.26
Pollination	Lu and Koide 1994	flowering duration	76%	0.57
Pollination	Lu and Koide 1994	fruits produced	200%	1.10
Pollination	Lu and Koide 1994	fruits produced	350%	1.50
Pollination	Lu and Koide 1994	fruits produced	20%	0.18
Pollination	Poulton et al. 2001	flowers per plant	113%	0.75
Pollination	Poulton et al. 2001	flowers per plant	90%	0.64
Pollination	Wolfe et al. 2005	pollinator visitation rates	100%	0.69
Pollination	Wolfe et al. 2005	seed set	167%	0.98
Food & Raw materials	Elliot et al. 2020	small mammal diet	80%	
Food & Raw materials	Willis 2018	edible mushroom market	US$42B/yr	
Water	van der Heijden 2010	reduction in nutrient leaching due to AMF	60%	

Table 1 Notes:

1) See Markovchick et al. 2023 Supplement S1 for an expanded list of studies and more detailed explanation. Ecosystem service categories are abbreviated from Costanza et al. 1997, see Markovchick et al. 2023 for details.
2) Absolute value of percent change seen (always an improvement, but sometimes the improvement is an increase, and sometimes it is a decrease, for example in disease severity).
3) Effect size is either the statistic provided in the paper (there are various ways of calculating this and not all mean the same thing, see Sullivan and Feinn (2012) for a summary), or calculated as ln(mycorrhizal mean / control) from the statistics provided in the publication (if no effect size was calculated in the paper). This measure of effect size has the advantage of being directly related to percent change (Pustejovsky 2017), which can be calculated using the following equation: $(e^{\ln(R)} – 1) \times 100\%$. For example, an effect size of 0 indicates a 0% change, 0.5 indicates a 65% change, and 0.75 indicates a 110% change in the mean between treatment and control (Pustejovsky 2017).

1. *Disturbance Regulation & Response*

This category includes boosting the ability of ecosystems to respond to environmental fluctuations and dampening the influence of disturbances on the integrity of the ecosystem. Mycorrhizas assist in site clean-up, vegetation return, and protection of plants against toxins at polluted sites (e.g. Wulandari et al. 2016). They reduce invasive vegetation (e.g. Rinaudo et al. 2010). Mycorrhizal fungi enhance plant water status, survival, and productivity, including during and after droughts (e.g. Querejeta et al. 2006; Kivlin et al. 2013).

2. *Erosion Control & Sediment Retention*

This service category includes retaining soil within an ecosystem. Mycorrhizas increase the stability of soils through entangling soil particles in a "sticky string bag" to form soil aggregates. These aggregates are structured by hyphae and enhanced by stabilizing substances that hyphae secrete, such as glomalin (Rillig & Mummey 2006; Nautiyal et al. 2019). As a result, mycorrhizas play critical roles in stabilizing soil and protecting it from surface water flows (Mardhiah et al. 2016) and wind erosion (Burri et al. 2013).

3. *Food & Raw Materials*

This category includes the portion of gross primary production consisting of food and raw materials. In addition to their use to promote crop production (Reddy et al. 2006; Rinaudo et al. 2010), 350 species of mushrooms (many of which are mycorrhizal fungi) are known to be used for food (Willis 2018). Many kinds of fungi, including some that are mycorrhizal, are used to create medicines, enzymes used in industry, and sustainable clothing, packaging, and construction materials (e.g. Bhat, 2000; Willis 2018).

4. *Gas & Climate Regulation*

This category includes regulating the chemical composition of the atmosphere, global temperature, and other climatic processes mediated by organisms. Clemmensen et al. (2013) found that a majority of boreal forest soil-stored carbon is in roots and root-associated microorganisms (including mycorrhizal fungi). Orwin et al. (2011) found that improved plant nutrient access due to mycorrhizal symbioses increased carbon sequestration. Fungal hyphae also produce exudates that promote the formation of soil aggregates, stabilizing soil and supporting continued carbon sequestration in the soil (e.g. Nautiyal et al. 2019). Mycorrhizas compete with saprotrophs (decomposers) for soil nutrients, reducing decomposition (decomposition releases carbon) and increasing soil carbon storage (Read & Perez-Moreno 2003; Fernandez & Kennedy 2016).

5. *Genetic Resources*

This category includes unique biological materials and products, and their sources. An enormous variety of medical compounds are derived from or produced by fungi (see Markovchick et al. Supplement S1). Mycorrhizal symbioses improve plant nutrition and enhance the active ingredients of medicinal plants (Zeng et al. 2013). The effects of fungal genetics likely cascade through ecosystems. For example, ectomycorrhizal fungi are linked via plant genetics to insects, lichens, pathogens, endophytes, and soil decomposing fungi and bacteria (Lamit et al. 2015). Given the role of fungi as foundational taxa that help to structure ecosystems (e.g. Tedersoo et al. 2014), their genetic diversity may be crucial to conserving and supporting the genetic diversity at other community levels and stabilizing our ecosystems (e.g. Hazard et al. 2017).

6. *Habitat & Biodiversity*

This category includes habitat for resident and migratory populations, a refuge for species and biodiversity. Nearly all plants depend on the presence of mycorrhizal fungi (van der Heijden et al. 2015). Fungal contributions to plant nutrition and performance cascade through ecosystems, influencing habitat quality and resource quantity for most terrestrial species. One recent modeling effort suggests that the biomass of organisms in the Serengeti would be reduced by half without just the phosphorus provided by arbuscular mycorrhizal fungi (Stevens et al. 2018). Another preliminary, smaller-scale model indicated that simply including appropriate mycorrhizal inoculation in restoration efforts could increase the useable habitat for an endangered bird from 0 to 1.2 hectares six years after restoration (Tracy & Markovchick 2020).

7. *Nutrient Cycling & Soil Formation*

This service category includes the processes involved in forming, cycling, storing, and processing soil and nutrients. With complex enzymatic capabilities that allow them to access nutrients bound in recalcitrant forms, mycorrhizal fungi can forage for nutrients and mine them (e.g. Fernandez & Kennedy 2016). They may also indirectly facilitate decomposition by free-living soil microbes as they forage for nutrients in soil organic matter (e.g. Talbot et al. 2008). Mycorrhizal fungi also structure soils and reduce nutrient losses (Rillig & Mummey 2006; Parihar et al. 2019), permitting retention of nutrients necessary to build fertile soils (van der Heijden 2010).

8. *Pest & Insect Regulation*

This category includes regulation of populations, such as insect pests, invasive vegetation, and disease. Mycorrhizas and endophytes play key roles in this area. For example, Karst et al. (2015) found that mycorrhizas increase monoterpene production, a key chemical defense against herbivory. Mycorrhizal fungi also reduce viral symptoms, disease and invasive vegetation (e.g. Miozzi et al. 2020; Reddy et al. 2006; Rinaudo et al. 2010). Mycorrhizal fungi also appear to share pest warning signals through underground networks, permitting a coordinated call that attracts insects that control plant pests (e.g. attracting parasitoids that reduces aphids in Babikova et al. 2013).

9. Pollination

This category is defined as moving and assisting floral reproduction. Our knowledge of fungal impacts on plant-pollinator interactions remains limited, and largely focused on arbuscular mycorrhizal fungi (Barber & Gorden 2015). However, these mycorrhizas can increase average flower number, flower mass, pollen tube length, seed production, nectar production and sugar content, pollinator visitation rates, and the number of fruits produced per plant (Aguilar-Chama and Guevara, 2012; Cahill et al. 2008; Gange & Smith 2005; Lu & Koide 1994; Poulton et al. 2001; Wolfe et al. 2005). Mycorrhizas could also assist plant reproduction under climate change in two ways: 1) they can decrease time to initial flowering and increase flowering duration, reducing potential mismatches between flowering and pollinator activity (Barber & Gordon 2015; Lu & Koide 1994), and 2) they can encourage clonal growth, which could assist plant survival if pollination is reduced or impossible (Botham et al. 2009).

10. Water Quality & Supply

This combined service category includes the regulation, retention, and cleansing of water. Mycorrhizas enhance nutrient retention in vegetation, mycelium and soils - decreasing leaching that negatively affects water quality (van der Heijden 2010). Mycorrhizal mycelia aggregate soil particles, improving soil porosity, and enhancing water infiltration and moisture retention (e.g. Augé et al. 2001; Rillig & Mummey 2006). They mediate hydrological functioning by modulating surface soil-to-water attraction and repellency (e.g. Rillig et al. 2010; Zheng et al. 2014). Mycorrhizal hyphae infiltrate bedrock and tiny soil pores to access water, and contribute to the soil-plant-atmospheric-continuum of water dynamics and nocturnal hydraulic lift of water to upper soil layers (Allen, 2009; Bornyasz et al. 2005; Querejeta et al. 2007).

A Special Note on Common mycorrhizal networks

Although the exact function of common mycorrhizal networks (the roots of separate plants linked by a network of fungal strands) is challenging to ascertain under field conditions, even critics recognize their existence in the field and demonstrated functions under controlled conditions (e.g. Karst et al. 2023). For example, these underground networks are known to share resources between trees, shrubs, and other understory plants in the field, with some plants known as mycoheterotrophs being entirely dependent on this setup (e.g. Karst et al. 2023; Selosse et al. 2006). Under laboratory conditions, the use of autoradiography, dye tracers, and air gap treatments provide convincing evidence that resources are shared via the connections between plants provided by mycorrhizal fungi, including carbon (e.g. Finlay et al. 1986; Brownlee et al. 1983; Wu et al. 2001), phosphorus (e.g. Finlay 1989), water (e.g. Warren et al. 2008; Plamboeck et al. 2007; Egerton-Warburton et al. 2007), and defense signals (Babikova et al. 2013). This ability to spread resources (Peay et al. 2016) in the field would reduce risk and increase the inherent stability of ecosystems the way that financial portfolios reduce the risk of investing (Schindler et al. 2015).

While trees communicate chemically all the time through the volatile organic chemicals they produce wafting through the air, research indicating communications and resources are shared through soil, root systems, and common mycorrhizal networks (e.g. Babikova et al. 2013; Bingham & Simard 2011; Simard et al. 2015) poses special new questions for the land and natural resources communities, due to the ability of land management actions to impact the soil community. If the ability of trees to communally send stronger insect control signals or share resources in times of need is impacted by current tree density reduction practices, as suggested by the scientific literature referenced herein, then the government would be liable for ignoring this large body of science, and the impact of its actions. Even the critics of the available current technologies acknowledge that given what we know about plant and fungal biology, these underground linkages, “should be common” (Karst et al. 2023), and the indications of the science are clear - this issue is not constrained to one or a few environments or biomes.

III. To comply with NEPA, the Forest Service must consider soil function, mycorrhizal interactions and impacts to mycorrhizal assisted ecosystem services in a detailed environmental analysis.

Many kinds of activities and disturbance can harm soil biota, including mycorrhizal fungi. Examples include the changes to microclimates and soil compaction caused by logging and thinning activities, the application of herbicides and pesticides, pollution deposition, and the presence of, and soil legacy left behind by, non-native vegetation (Wiensczyk et al. 2002; Hartmann et al. 2014; Meinhardt & Gehring 2012; Koziol & Bever 2017; Helander et al. 2018). Appropriately protecting and restoring native mycorrhizal diversity and abundance offers a crucial tool to support forest resiliency. Conversely, when mycorrhizae are not protected from these effects, or are not appropriately restored, this can negatively impact forest regeneration and resiliency for many years. Unfortunately, soil biota like mycorrhizal fungi are frequently ignored in forest planning and projects, despite Forest Service policies requiring their protection (Markovchick et al. 2023), and a regulatory and legal framework requiring their consideration and mitigation of impacts to them.

The Forest Service may not ignore topics if the information is uncertain or unknown. Where information is lacking or uncertain, the Forest Service must make clear that the information is lacking, the relevance of the information to the evaluation of foreseeable significant adverse effects, summarize the existing science, and provide its own evaluation based on theoretical approaches. As such, the Forest Service has a mandatory duty to analyze the direct, indirect and cumulative impacts of the proposed action on soil function, mycorrhizal interactions and impacts to mycorrhizal related ecosystem services in a detailed environmental analysis.

A. Adequately assessing and disclosing direct, indirect, and cumulative impacts, including detailed, site-specific information

The Forest Service must analyze the direct, indirect, and cumulative impacts of a proposed action. Colo. Envtl. Coal. v. Dombeck, 185 F.3d 1162, 1176 (10th Cir. 1999); see also 40 C.F.R. § 1508.25(c) (1978) (when determining the scope of an EIS, agencies "shall consider" direct, indirect, and cumulative impacts). Cumulative impacts are "the impact[s] on the environment which result[] from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency (Federal or non-Federal) or person undertakes such other actions." 40 C.F.R. § 1508.7 (1978). Forest Service regulations define reasonably foreseeable future actions as "[t]hose Federal or non-Federal activities not yet undertaken, for which there are existing decisions, funding, or identified proposals." 36 C.F.R. § 220.3.

Further, site-specific analysis is crucial to NEPA's goal of ensuring informed and science-based decision-making. The Forest Service must provide sufficient information for the public to understand the scope of the proposed activities. In order to fully comply with NEPA, the Forest Service must adequately assess and disclose impacts of the proposed action on soils, and particularly mycorrhizae, including impacts from forest road construction, vegetative management actions such as commercial harvest, non-commercial thinning, controlled burning and related actions (i.e. fireline construction). Such disclosure must address each of the mycorrhizal ecosystem services we describe above and the potential impacts to common mycorrhizal networks, unless the agency can demonstrate their absence in the project area.

B. Reliance on soil [best management practices, resource protection measures or design features][1]

The Forest Service cannot rely on best management practices, design features or resource protection measures as a rationale for omitting proper analysis. Even if such practices or measures have a demonstrated history of success, the agency cannot assume they will be

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[1] Note here the Forest Service uses different terms depending on the specific projects and often uses one or more of these terms: best management practices, resource protection measures or design features.

implemented correctly 100 percent of the time, or that they will be 100 percent effective. As such, the Forest Service must disclose the environmental impacts of each action alternative without assuming 100 percent BMP efficacy, either by providing the worst-case scenario or a range of effectiveness.

C. Adhering to applicable directives per the Forest Service Manual

The Forest Service Manual (FSM) includes a specific objective that “Ecosystems are ecologically or functionally restored so that over the long term they are resilient and can be managed for multiple use and provide ecosystem services, including but not limited to carbon storage and sequestration.” (FSM 2020.2). Further, the manual directs that “Responsible soil stewardship [promotes and sustains], biological and hydrologic function, [and that], chemical, physical, and biological soil properties [will all be used to] assess existing soil condition for watershed condition and ecological assessments.” (FSM 2550.3). Yet, a main driver of restoration, resiliency, and ecosystem services including hydraulic lift and water infiltration, retention, and efficient use by vegetation - mycorrhizal fungi - are nowhere to be found in the forest plan or project. In fact, no biological aspects of the soil appear to be monitored.

In addition, the manual defines biological properties that support “the productive capacity of the land, its ecological processes, such as hydrological function of watersheds, and… ecosystem services” as part of desired soil conditions. (FSM 2550.5). This in fact seems to specifically point to soil biota such as mycorrhizal fungi as something to be monitored and supported.

The Forest Service also directs the following: “Use adaptive management (FSM 1905) to design and implement land management activities in a manner that achieves desired soil conditions and objectives….,” monitor soil conditions and trends to ensure that soil and water conservation practices are implemented and effective…, [and] “Determine how changes in soil properties will affect desired soil conditions and objectives related to ecosystem function.” (FSM 2551.03). Yet, it is unclear how the agency could possibly meet this direction without monitoring, protection and restoration of mycorrhizal fungi, given the extensive evidence of the roles they play in ensuring ecosystem services, productivity, and unimpaired future functioning of the land in all the ways laid out in the Forest Service Manual. In fact, the manual section on monitoring calls for monitoring sufficient “to determine the soil condition and the cause and effect relationships associated with those conditions….” [and] “Use soil quality monitoring to validate and refine management decisions.” (FSM 2551.13) The information collected allows land managers “to determine if land management plan desired conditions are being achieved.” *Id.* This section clearly states, “The major objective of soil quality monitoring is to ensure that ecologically sustainable soil management practices are being applied…. “ [and] “Monitoring is conducted to detect changes in physical, chemical, or biological soil properties caused by management activities.” *Id.* Since no monitoring of mycorrhizal fungi occurs, much less monitoring sufficient to determine how management actions are impacting this part of the ecosystem, clearly the intent of the manual is not being carried out.

The manual also states that “current science and key soil functions and attributes/indicators/soil properties representing those functions” should be considered in developing land management monitoring, standards and guidelines. (FSM 2551.3). Despite this, at least one entire Kingdom which helps to determine soil functioning, and enormous scientific evidence demonstrating the key soil functions that mycorrhizal fungi in particular contribute appears to be entirely ignored.

“The focus of forest plan monitoring is to gauge the progress toward achieving or maintaining the desired conditions and objectives.” (FSM 2551.61). When these desired conditions and objectives, as set forward by the FSM, clearly include key biological players in soil function such as mycorrhizal fungi, how can they be resoundingly ignored?

Not only does the FSM clearly state in all the passages above, that key soil biology such as mycorrhizal fungi should be the focus of desired conditions, standards and guidelines, and monitoring. The section of the FSM that deals with invasive vegetation also makes it clear that these key players must be monitored, protected, and restored. The manual also clearly states that objective must be to

> limit the adverse effects of those infestations on native species, human health, and other National Forest System resources [and] implement restoration, rehabilitation, and/or revegetation activities following invasive species treatments to prevent or reduce the likelihood of the reoccurrence or spread of aquatic or terrestrial invasive species.

(FSM 2902). Based on the overwhelming scientific evidence, this simply cannot be achieved without restoring diverse communities of native mycorrhizal fungi appropriately paired to site conditions and planting materials after most invasions by exotic vegetation.

In fact, the Forest Service clearly acknowledges that integrated pest management requires “an ecologically-based holistic strategy that relies on natural mortality factors, such as natural enemies, weather, and environmental management, and seeks control tactics that disrupt these factors as little as possible [specifically including] biological…techniques.” (FSM 2902). Based on an overwhelming amount of the best available scientific information, mycorrhizal fungi are key to both managing invasive vegetation, and restoring full function and diversity after invasions. Yet, again, they appear nowhere in this project or forest plan.

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