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Enriching Log Landings to Sustain Native Bees and Other Pollinators: A Guide for Practitioners

Lauren S. Pile Knapp, Aliza Fassler, Connor Crouch, Morgan Davis, Daniel C. Dey, Brooke Hagarty, John Kabrick, David King, Benjamin O. Knapp, Susannah B. Lerman, Deborah Page-Dumroese, Will Rumpf, and Sloane Scott



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Abstract

Log landings—designated staging areas for logs during timber harvests—can be enriched as habitat for native bees and other pollinator species, turning often degraded areas into local hotspots for biodiversity. Pollinators provide an important ecosystem service for economically important agricultural crops and for trees and plants, but populations are declining due in large part to habitat loss. Enriching soils and seeding native plants on log landings (beyond traditional erosion mitigation practices) can provide pollinator habitat on the modern landscape. This guide provides information and resources for developing log landing enrichment projects in actively managed forest landscapes based on projects on log landings in midwestern national forests. The projects tested techniques to mitigate soil compaction, seed and monitor the success of native plant species that support pollinators, and reduce invasive plants with the goals of increasing floral and nesting resources for native pollinators and improving aesthetics.

Keywords: soil compaction, biochar, subsoiling, native plants, invasive plants, seed mix, plant-pollinator interactions, timber harvest, active forest management, wildlife, open forests

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Cover photo: Native bumblebees (*Bombus impatiens*) on *Bidens aristosa*. USDA Forest Service photo by Lauren S. Pile Knapp.

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EXECUTIVE SUMMARY

Habitat loss and other anthropogenic factors are driving declines in populations of pollinators such as native bees. Timber management can indirectly benefit pollinator habitat by increasing light in the forest understory, favoring pollinator-preferred plants for forage and exposing soil for nesting. Managers of forest lands across the United States are interested in actively creating pollinator habitat by modifying current timber harvesting operations to encourage native plant establishment and growth. Log landings, small patches of land that are heavily disturbed during harvesting operations, can serve as starting points for pollinator enrichment projects. Coupling native plant seeding with log landing soil restoration can greatly benefit native bees and other pollinators, especially when multiplied across a landscape. Because log landings are prone to soil compaction and invasion by non-native plants, soil restoration treatments and seeding may be needed to establish a native plant community that provides high-quality pollinator habitat. Soil restoration treatments, such as place-based biochar, also provide an opportunity to take advantage of low-value woody residues that are usually discarded or open burned. Biochar application can reduce compaction, increase porosity, retain nutrients, and sequester carbon. This guide is a resource for managers seeking to simultaneously rehabilitate log landings and enrich habitat for native bees and other pollinators. We provide examples and lessons learned from the Pollinator Habitat in Log Landings (PHiLL) project developed through collaboration on three midwestern national forests.

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THE ECOLOGICAL NEED FOR ACTIVE FOREST MANAGEMENT TO SUSTAIN NATIVE POLLINATORS

Globally, alarm is growing over the significant decline in insects—particularly pollinators—due primarily to the loss of quality habitat, a change that has economic and ecological impacts. Forests are reservoirs of pollinator biodiversity, hosting unique, forest-associated species. Loss of forested land, especially open-canopy systems (Hanberry et al. 2020), is a driver of pollinator declines.

In the United States, national forest monitoring programs reveal that contemporary forests are generally young (i.e., less than 100 years old), densely stocked, and lacking in species and age-class diversity (Fig. 1). These forests differ from pre-colonial conditions, where landscapes were more diverse in composition and structure, characterized by a heterogenous mosaic of dense mature and old growth forests with canopy gaps, open forests (i.e., woodlands and savannas), and grasslands. This mosaic was created and maintained by natural disturbances (e.g., drought, wind and storms, insects, diseases, and wildfire) and human-initiated fire.



Figure 1.—Overly dense, mature, oak-hickory, closed-canopy forest. USDA Forest Service photo by Daniel C. Dey.

These landscapes contained a full range of habitat conditions and supported a diverse array of wildlife, ranging from species associated with closed-canopy forests with large trees and complex woody structure to species that thrive in open habitats of early seral forests, woodlands, and savannas. The lack of suitable, abundant, and available habitat for pollinator species that depend on open forests has negative implications for native biodiversity and ecosystem function.

Open forests are characterized by a simple woody structure consisting of a mature tree overstory (often of oaks [*Quercus* spp.] or pines [*Pinus* spp.]), little to no midstory, and understory trees and shrubs that are often post-fire sprouts. Overstory trees occur at lower densities than in closed-canopy forests. Low tree density and the lack of a woody midstory layer allow more sunlight to reach the forest floor, where a high diversity of herbaceous species proliferate. Frequent surface fire, which is often used to maintain open forest structure, further promotes a diverse and

abundant herbaceous ground flora. This open structure is often preferred by bats and songbirds that forage on the diversity of seed and soft mast produced in these habitats. The rich ground flora is also a productive habitat for a diversity of insects, including pollinators.

Restoring open forests and increasing landscape-level diversity—objectives that can benefit populations of native bees and other pollinators—can be accomplished through active forest management using prescribed fire and silvicultural practices (e.g., tree thinning and harvesting). Log landings used in timber harvest operations can play a key role in restoring pollinator habitat. Through post-harvest rehabilitation of the soil and vegetation, these relatively small yet highly impacted areas can be focal points for restoration. Mitigation of compacted soils on landings provides an opportunity to grow quality open habitat for pollinator insect species. Further, log landings created during restoration of open forests provide opportunities to connect habitat patches, introduce native plants that support healthy and viable pollinator populations, and serve as islands of refuge for pollinator colonization of newly restored habitat.

What Are Log Landings?

Log landings are open areas, typically adjacent to forest roads, that are constructed during harvest operations to gather and stack logs from the surrounding forest before being loaded onto log trucks for transport (Fig. 2). Because harvesting equipment can cause soil compaction and erosion, best management practices (BMPs) provide guidance on landing quantity, size, and location with respect to soil properties and topography. For example, BMPs limit log landing construction to periods when soils are in good condition for heavy equipment use (e.g., not too wet).



Figure 2.—Recently closed log landing on the Mark Twain National Forest, Poplar Bluff, Missouri. USDA Forest Service photo by Lauren Pile Knapp.

Log landings are purposefully small (0.25 to 0.75 acres) to minimize their footprint. Even so, the highly localized effect of vehicle traffic and log stacks on forest soils can be disproportionately large. Recovery from soil compaction may take several decades, even with mitigation treatments. Highly compacted soils make it difficult for plants and trees to establish and grow, and the few plants that do establish are often invasive or have low ecological value for native pollinators. Consequently, it is preferable to reuse log landings during subsequent harvest entries to minimize

additional impacts across the landscape. Although reusing dedicated landing sites and skid trails during timber harvests may have long-term soil impacts, doing so restricts heavy machine traffic to specific areas of a forest and minimizes the areal extent of soil and vegetation disturbance. Areas designated as log landings typically remain open and can provide long-term habitat for local wildlife, such as songbirds (Tucker and Olson 1994). Log landings can also offer a unique opportunity to increase resources for native pollinators (Case Study 1).



Case Study 1
Pollinator Habitat in the Poconos Region

A compelling example of log landings as pollinator habitat comes from the Poconos region of the Central Appalachian Mountains (Lee et al. 2021). Researchers from Indiana University of Pennsylvania and the Center for Pollinator Research at Pennsylvania State University evaluated pollinator use in both log landings and recently harvested forest stands adjacent to the log landings. In this study, researchers examined log landings from timber harvests conducted within the last 6 years; these landings had not been seeded or otherwise modified for pollinators. Every 3 weeks from June to September, observers counted butterflies and the abundance of various bee groups such as carpenter bees (*Xylocopa virginica*), medium-sized native bees (e.g., *Osmia* spp., *Megachile* spp.), and small black bees (e.g., *Ceratina* spp.).

Results showed that log landings had more than twice as many bees than the adjacent timber harvest sites (1,389 bees versus 363 bees), 5 times as many butterflies (259 butterflies versus 51 butterflies), and 14 times as many flowering plants used by pollinators (i.e., floral resources). The high pollinator density in log landings was largely driven by the abundance of floral resources. This research adds to the growing body of literature demonstrating that active forest management can provide important habitats for wild pollinators.

Why Enhance Log Landings for Native Bees and Other Pollinators?

Active forest management seeks to stabilize and often improve quality habitat for native bees and other pollinators—flies, wasps, butterflies, moths, and beetles—by restoring ecological communities and promoting the establishment of native plants that provide a diverse range of ecosystem goods and services. Many species of native bees respond positively to the outcomes of silvicultural treatments such as early successional habitats created by regeneration harvests or open forest restoration created by thinning and burning, but log landings are often considered degraded habitats due to soil compaction and establishment of ruderal (i.e., weedy native) or invasive plants. However, deliberate management to improve log landings can promote pollinator diversity and abundance by enriching diversity and abundance of pollinator-preferred plant species (Case Study 2). Enrichment of log landings can promote diverse pollinator habitat, provide localized seed sources for native plant establishment into the forest interior, reduce the abundance and impacts of invasive plants, increase carbon storage and water infiltration, beautify transportation corridors, and create spaces for thoughtful dialog about active forest management for native pollinators.



Case Study 2
PHiLL Project: Pollinator Habitat in Midwestern Forests

Although log landings are generally considered degraded habitats because the use of heavy equipment results in soil compaction and removes vegetation, these spaces offer opportunities for open, floral-rich habitat improvement.

Managers at three midwestern forests in the National Forest System of the U.S. Department of Agriculture, Forest Service (Fig. 3) sought to provide native pollinator habitat on log landings with similarly degraded conditions. Independently, each forest had tested approaches to establishing native plants, but efforts often failed or success was variable and unpredictable. To improve results, a multidisciplinary team was formed that included specialists from the three national forests, researchers from the Forest Service Northern Research Station, and university partners.

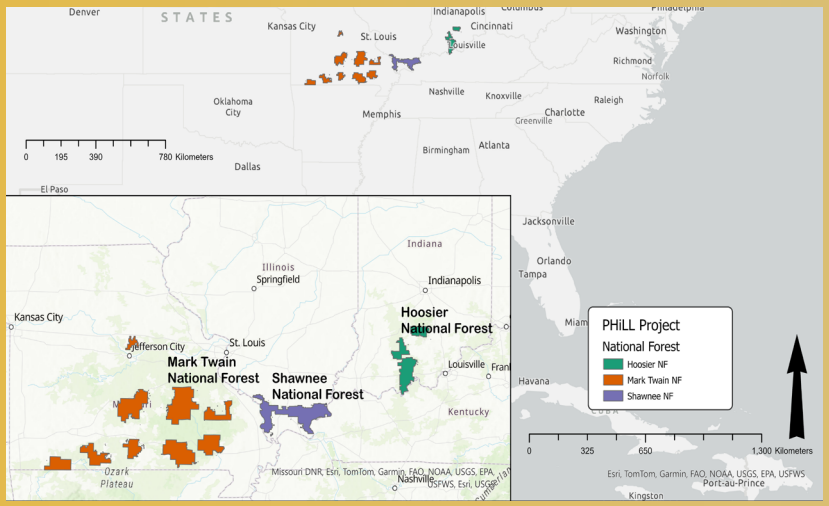


Figure 3.—Map of the three national forests where the Pollinator Habitat in Log Landings (PHiLL) project was conducted.

The team initiated the Pollinator Habitat in Log Landings (PHiLL) project that, from its onset, intentionally co-produced actionable science. Regional program managers and specialists on other national forests were also invited to participate and share their perspectives. Approaches and treatments were developed through thoughtful deliberation and by drawing on the experiences and resource specialties of the collaborative group. The final experimental design included subsoiling to reduce compaction, biochar to improve soil conditions, and native seeding to promote plant diversity and abundance using a factorial design that allowed the comparison of outcomes across a variety of site conditions representative of log landings in the southern Midwest (Fig. 4).

Initial results revealed that 8,718 bees from 99 different species were observed in the first growing season following implementation on log landings that were part of the PHiLL project. Species recorded included bee species of conservation concern, including the American bumblebee (*Bombus pennsylvanicus*). On landings treated to reduce soil compaction and seeded with a native pollinator seed mix, 89 species were observed compared to 81 species observed on untreated control landings. The plant species used most frequently by bees on seeded landings were plains coreopsis (*Coreopsis tinctoria*) and black-eyed Susan (*Rudbeckia hirta*). Together, these two plant species provided pollen and nectar for 34 bee species.

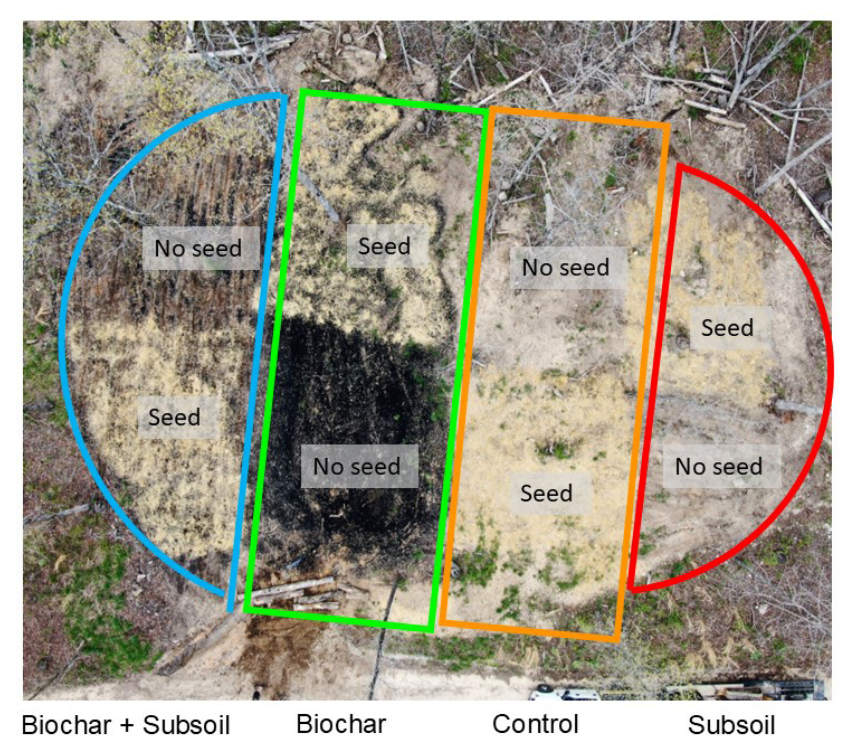


Figure 4.—Experimental design of a treated PHiLL log landing with four seeded and unseeded subplots: biochar and subsoiling combined, biochar alone, a control, and subsoiling alone. Courtesy image by Will Rumpf/University of Missouri.

THE BIOLOGY AND ECOLOGY OF NATIVE BEES

Bees play a critical role in ecosystem health and sustainability across the globe. Although domestic honeybees (*Apis mellifera*) introduced from Eurasia provide humans with honey and crop pollination, more than 4,000 native bee species in the United States also provide essential pollination services and are wildlife species in need of conservation attention. Native bees range in size from smaller than a grain of rice to 1 inch and range in color from yellow to brown, red, black, green and even blue (Fig. 5).

Pollen and Nectar Needs

Most native bee species meet their nutritional needs by foraging on the nectar and pollen of flowering plants (referred to hereafter as "floral resources"; Leach and Drummond 2018). Plants produce nectar, a sugar-rich liquid designed to attract pollinators, secreted by flower nectaries. Pollen is produced by the male part of a flower, called an anther, which contains the plant's male gametes. When collecting nectar, pollinators other than bees (such as wasps and butterflies) accidentally brush against the plant's anthers and transport pollen to other plants. When the pollen of one plant species is moved to a different plant of the same species, the critical service of pollination is accomplished.

Bees are unique: They collect pollen deliberately with specialized organs on their legs or elsewhere to feed their young. Female bees provide growing bee larvae a "pollen loaf" containing nectar, pollen, and gut microbial symbionts that is enclosed with the larvae in a nest cell (Leach and Drummond 2018). Pollen is also a source of protein for egg development in adult female adult bees (Leach and Drummond 2018, Michener 2000). This active pollen collection by



Figure 5.—The diversity of native bee species: ligated furrow bee (*Halictus ligatus*) (A), a male masked bee (*Hylaeus* sp.) (B), a blue mason bee (*Osmia* sp.) (C), and a bicolored striped sweat bee (*Agapostemon virescens*) (D). Courtesy photos by Mike Amato.

native bees provides more efficient and effective pollination services to a diverse number of plant species than the incidental pollination that happens when other pollinators forage for nectar.

Bees pollinate flowers, trees, and other plants that then provide food and habitat for other creatures, including humans. Bees' role in pollinating agricultural crops is invaluable, but native bees and many other pollinating species are declining in range and abundance due in large part to habitat loss. Fewer pollinators mean fewer fruits and seeds of the plants they pollinate, impacting people and wildlife. Increasing the abundance, diversity, and availability of floral resources throughout the growing season and protecting and enhancing bee nesting sites may help to reverse declines in native bee populations.

Specialist Versus Generalist Bees

Some bee species require certain plants for pollen and nectar, while other bee species are generalists and use an array of available flowers and plant species. The dependence on particular plants by specialist bee species is an important consideration for habitat enrichment projects. A specialist, or oligolectic, bee feeds its offspring from a single plant species or a closely related group of plants such as species within a single genus. For example, bumblebees (*Bombus* spp.) are considered generalists and will collect pollen from almost any flower present, but some mining bees (*Andrena* spp.) are highly specialized and exclusively associated with plants in a single family (e.g., *Asteraceae*) or even limited to a single plant species. Specialist bees may rely on less common native plant species. Therefore, the abundance, diversity, and presence of specific plant species influence the abundance, diversity, and presence of native bees at a given site. See Appendix 2 for online resources on plants that serve as hosts for specialist bees.

Foraging Distance

Bee diversity and abundance are influenced by both local resources and conditions up to 1.25 miles away. Bees are "central place" foragers; they collect food and nest-building resources and return to a single location. The distance bees forage for floral and nesting resources relates to body size. For example, large bumblebees can travel up to 1.25 miles from their nest site, while small sweat bees regularly forage within 165 feet of their nest. Therefore, bee community abundance and diversity depend on the distance and connectivity between nesting habitat and floral patches (Lonsdorf et al. 2009).

Nesting Habitat

A lack of suitable nesting resources can limit bee populations (Potts and Willmer 1997). Suitable nesting sites include well-drained soils for ground-nesting bees and pithy stems or soft wood for cavity nesters (Cane 1991, Michener 2000).

In North America, it is estimated that 64 to 80 percent of native bee species are ground-nesters (Cane and Neff 2011, Harmon-Threatt 2020) that spend most of their lives underground overwintering as prepupa. During the growing season, adult bees emerge to mate and forage for a period that is short compared to their belowground development. Nest site selection for ground-nesting bees varies by species and is determined by a combination of many abiotic and biotic factors. These include soil texture, depth, compaction, moisture, and temperature, as well as slope, vegetation cover, floral resource availability, presence of other members of the same species, and natural enemies. In contrast, cavity nesters excavate nests in coarse woody debris or in plants with soft pithy stems, although some cavity nesters will "rent" existing cavities rather than build nests of their own.

Active bee foraging is influenced by bees' life history and by the phenology and composition of the flowering plants they depend on. Different bee species have specific phenological adult emergence patterns and live for a few weeks to months following emergence. Some species emerge early in the growing season, while other species emerge much later. Plant communities with limited availability of floral resources (e.g., few summer flowering species) do not support diverse bee communities, and communities dominated by one or a few flowering plants benefit only a few bee species. For example, dense flowering by the invasive sericea lespedeza (*Lespedeza cuneata*) can monopolize the attention of bees and inhibit the reproductive success of desirable native plants (Woods et al. 2012). Invasive plants can limit the establishment and growth of native plants and therefore reduce floral resource availability throughout the growing season. The quality of floral forage and availability of preferred plant species affect overall bee fitness and the quality of their pollination (Woodard and Jha 2017).

PLANNING: FOUR STEPS BEFORE STARTING A LOG LANDING ENRICHMENT PROJECT

Increased floral diversity and abundance generally are associated with increases in bee community diversity and abundance. Local and landscape factors resulting from active forest management can impact native bee habitat throughout a forest and also at a log landing. These factors include the silvicultural treatments applied, the harvest methods used, and the handling of timber residuals. Specifically at log landings, the degree of soil compaction and the establishment and growth of plants that support diverse bee communities can impact outcomes. Consideration of these factors can inform strategies for managing bee habitat on log landings.

The following steps can help practitioners assess a log landing site for an enrichment project. See also Appendix 1 for a sample planning and assessment prescription worksheet.

Step 1: Assess Log Landing Condition

- **What silvicultural system was used?** Generally, silvicultural practices that increase light and soil temperatures enhance the development of bee eggs and larvae and promote growth of herbaceous plants that serve as food sources for bees. Numerous studies (e.g., Favorito et al. 2023, Hanula et al. 2015, Mathis et al. 2021, Mullally et al. 2019, Odanaka et al. 2020, Proctor et al. 2012, Roberts et al. 2017) have shown that understory bee abundance and diversity are higher in recent harvests that create open-canopy conditions, like clearcuts, although it appears even single-tree selection systems can increase bee abundance and diversity (Nol et al. 2006). As such, silvicultural practices that enhance bee habitat may have a synergistic effect on the success of log landing enrichment.

- **How and where were trees processed—in the woods or at the landing?** Whole-tree harvests involve the transportation of the entire tree to the landing for processing, resulting in non-merchantable material including branches, twigs, and bark being deposited on the landing. Most native bees are soil nesters, so large quantities of slash (i.e., coarse woody debris produced from logging activities) can prevent bees from accessing bare soil where they excavate their nesting chambers. Thick layers of slash on landings also inhibit the establishment and growth of plants.

  In contrast, in-woods processing (removal of treetops and lateral branches during felling) leaves woody material scattered in the forest interior, reduces the amount of slash at the landing, and therefore helps to provide nesting opportunities for cavity-nesting bees and other wildlife species on the landing (Schnepf et al. 2009).

- **Was bark removed and retained at the landing?** Mulch layers on log landings influence plant and pollinator communities. For example, debarking of pine trees prior to loading for transportation can result in a large amount of bark at the log landing that is either distributed across the landing or piled.

  Typically, using harvest residue as mulch or a "slash mat" during harvest is intended to mitigate erosion and compaction on landings. When slash mats are used during operations, the downward force of machinery is distributed over a wide area and reduces direct soil compression. Slash mats also reduce erosion by protecting the soil from direct impacts of raindrops and slowing water movement over the surface of the soil. However, retaining thick slash mats on log landings after timber operations have ceased can inhibit the germination and growth of native plants, reduce ground-nesting bee resources, and reduce fertility in nitrogen-limited soils. Slash mats can also insulate the soil, moderating temperature swings and limiting freeze-thaw cycles that aid in the natural rebounding of compacted soil.

- **How isolated is the landing? Is there habitat nearby?** The surrounding landscape matrix also shapes the bee community at a log landing. An individual log landing exists among a patchwork of forest stands that differ in patch sizes, vegetation composition, configurations, and connectivity with other surrounding stands (Fig. 6). Log landings nested in a landscape of mature and homogeneous forest with little disturbance or in a highly fragmented anthropogenic or agricultural landscape may benefit from habitat enrichment for bees.

- **How large is the landing?** Although larger pollinator plantings are associated with greater increases in bee abundance and diversity, there is a threshold beyond which bee abundance and diversity do not increase with area. Bees use resources at the forest edge, and extremely large openings may isolate them from these edge resources. Research on forest openings in the U.S. Great Lakes region suggests that bee abundance peaks in openings from 0.24 to 0.37 acres in size (Cunningham-Minnick et al. 2024). Even small openings of 0.1 to 0.2 acres can support diverse bee communities (Mullally et al. 2019, Roberts et al. 2017), and small landings may be suitable for pollinator enhancement and more cost-effective than larger openings.

  Regardless of size, benefits for native bees are limited unless the landing is within a matrix that includes open habitat such as early successional forest created by regeneration harvests or open woodlands or savannas with scattered trees. Bees are less likely to colonize small landings isolated from open habitats, and these landings are unlikely to have enough resources to support diverse and abundant native bee communities.

Step 2: Assess Soil Condition

Soil is the foundation of high-quality pollinator habitat. Soil influences plant abundance and diversity, both of which are key for ground-nesting bees throughout their life cycle. Successful reproduction of ground-nesting bees relies on secure nests, which provide shelter for adult female bees. Soil condition following timber harvest can affect nesting resources for ground-nesting bees and the growth of plants that provide floral and nesting resources for the broader pollinator community.

Soil Compaction

Severe soil compaction and loss of organic matter after timber harvesting can have long-term impacts on water infiltration and storage, erosion potential, gas exchange, nutrient cycling, microbial activity, and plant growth (Luckow and Guldin 2007, Ponder 2007). Signs that remediation is needed include obvious erosion, measured compaction, and delayed vegetation reestablishment.

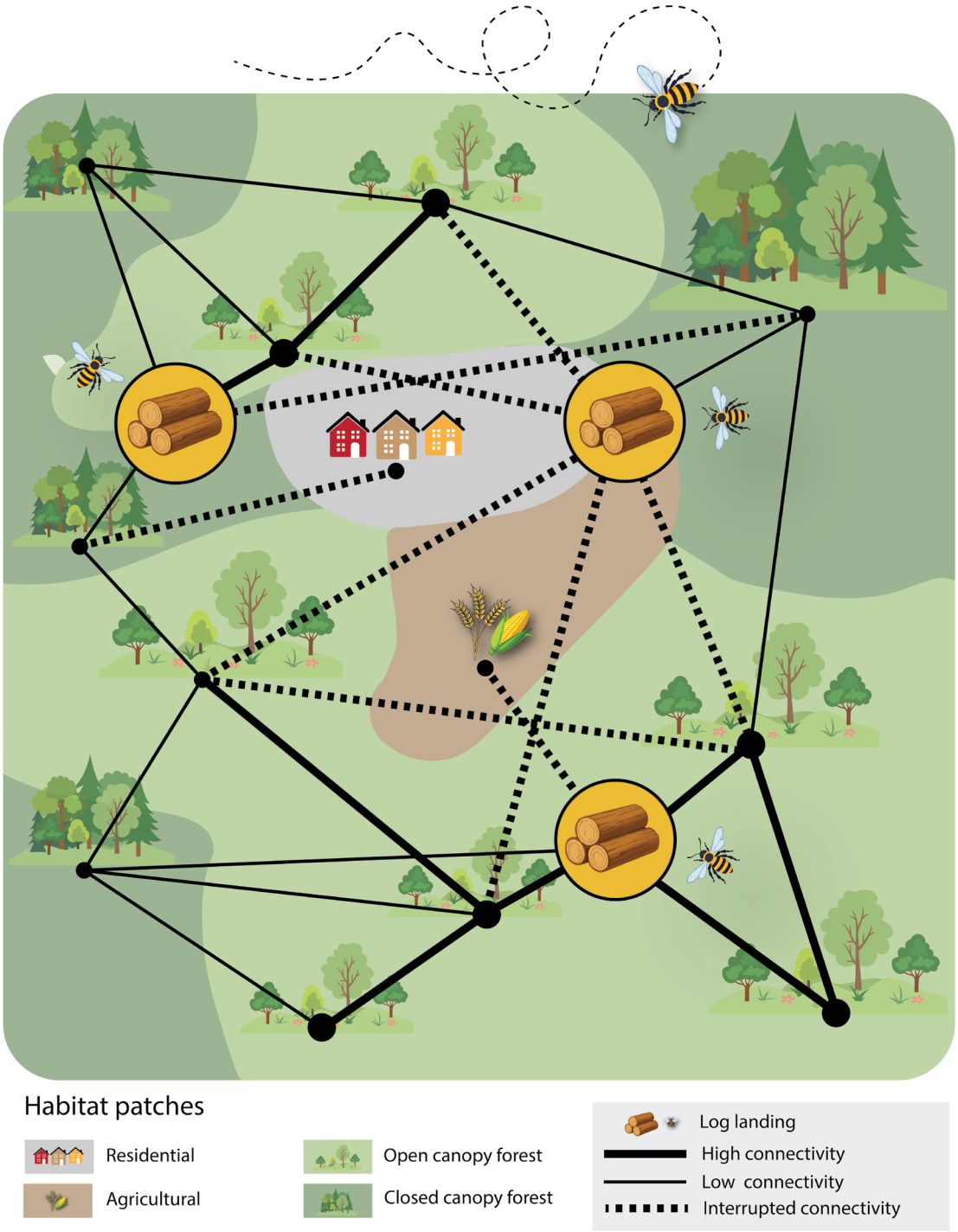


Figure 6.—Simplified representation of forest connectivity for native bees highlighting the importance of connecting log landings to other open forest habitat patches. Thin lines show lower connectivity of open-canopy forest habitats to closed-canopy forest habitats, thick lines show areas of high open-canopy habitat connectivity, and dashed lines show areas of connectivity interrupted by human development.

Although some bee species may prefer highly compacted areas, such as ATV trails, most ground-nesting bee species require soil that is soft enough to allow digging but compact enough to hold the structure of nest tunnels. Some studies suggest that high levels of compaction are negatively associated with ground-nesting bee abundance (Potts and Willmer 1997, Sardiñas and Kremen 2014).

Some pre-harvest soil mitigation practices to avoid compaction can also negatively impact ground-nesting bees. For example, the practice of removing the soil surface and storing it nearby is done to expose the subsurface soil horizons that are more suitable for heavy vehicle traffic (Hogan and Drake 2009). Although the surface soil is replaced after harvesting is complete, the removal can dramatically alter ground-nesting bee resources by disturbing the soil and exposing lower soil horizons.

Soil Properties

Evaluating the soil properties of log landings, such as texture and drainage, can minimize soil damage (e.g., compaction) prior to harvesting, and post-harvest assessment can inform decision making regarding log landing soil compaction and mitigation treatments. Signs that remediation is needed include obvious erosion, measured compaction, and delayed vegetation reestablishment.

Soil bulk density refers to soil mass per unit of volume and indicates the degree of soil compaction. Compaction compresses the large pores in soil and reduces the overall pore space, which restricts gas exchange, infiltration, water storage, and root growth and reduces overall soil health. Monitoring and managing soil bulk density are crucial for reestablishment of native vegetation on log landings.

Soil texture determines the bulk density threshold above which the soil is considered compacted. Finer textured soils tend to be more susceptible to compaction, which is reflected in their lower bulk density thresholds (Table 1). Sandier soils have higher bulk densities before they are considered compacted because coarse-textured soils retain a certain amount of pore space even when compacted, allowing roots, water, and gasses to pass more easily. Rocky soils have greater resistance to compaction and rutting than soils of similar texture without coarse, rocky fragments. Rocks in soil act similarly to a graveled road; they redistribute downward force and protect the soil and pore space around the rocks. Rocky log landing sites are preferable for harvest operations because they will likely rebound more quickly or resist severe compaction entirely.

Table 1.—Assessment criteria for evaluating the level of soil compaction as a measure of bulk density. Soil with low bulk density needs no action before planting, soil with medium bulk density would benefit from mitigation before planting, and soil with high bulk density needs mitigation before planting.

	Bulk density (g/cm)		
Surface texture[a]	**Low**	**Medium**	**High**
Silt loam, silty clay loam, silty clay, clay	<1.40	1.40–1.45	>1.45
Loam, clay loam	<1.45	1.45–1.55	>1.55
Sandy loam, sandy clay loam, sandy clay	<1.55	1.55–1.75	>1.75
Loamy sand, sand	<1.75	1.75–1.85	>1.85

[a] Estimated in the field or determined with SoilWeb or Web Soil Survey.

Ways to Assess Soil Condition

- **Use soil information and web applications—**Soil information from the Soil Survey Geographic Database (SSURGO) is essential for identifying soils in log landings at high risk of compaction and disturbance. Useful tools for accessing and using SSURGO data to assess soil conditions include SoilWeb, an interactive map interface that enables users to do cursory soil assessments in a specific field location (mobile friendly), and Web Soil Survey, a comprehensive tool that provides maps and detailed reports about soil properties and limitations for vegetation growth or water infiltration (works best on a computer). Both tools provide information about surface texture, drainage, vulnerability to rutting, and compaction useful for identifying potential log landings for enhancement.

- **Conduct disturbance monitoring—**Disturbance monitoring relies on inspection of soil horizons and is used to determine the degree, extent, duration, and distribution to which soil has been disrupted. Disturbance monitoring can be as simple as digging two sample holes—one on the log landing and one on an undisturbed reference site (such as the forest interior)—and noting the changes in texture and color of horizons between the samples. Whether surface horizons have been mixed, disturbed, or entirely removed will be obvious in reference comparisons (Fig. 7). A disturbed horizon will lack natural aggregation and contain woody debris. A compacted soil surface horizon may have platy structure and could

also have changed in color from reddish brown to gray if conditions have been wet for long periods.

Visual inspections of disturbed soils for sheet erosion (occurring across a wide area) and rill erosion (occurring in a shallow channel) can indicate a lack of soil structure and protective vegetation cover (Fig. 8). Signs of sheet and rill erosion are assessed more effectively after large or intense rain events.

- **Determine soil bulk density and compaction**—Soil bulk density sampling can be performed at the same time as disturbance monitoring using a variety of approaches. For example, pushing a rod or shovel into disturbed and undisturbed soils provides an indication of whether the disturbed soil is compacted and the depth of the compaction. For more precise sampling, a slide hammer bulk density sampler (e.g., Arts Machine Shop, American Falls, ID, USA) or metal rings hammered into the soil at various depths can be used (Fig. 9). Field equipment, a scale, and a drying oven are needed to gather detailed data on bulk density measurements, but the process is relatively simple.

Information on soil textures for a site can be found via SoilWeb and used in combination with bulk density sampling to inform remediation needs designed to improve soil properties for plant establishment and ground-nesting bees.



Figure 7.—Mixed and displaced surface organic horizons on a harvest unit. USDA Forest Service photo.



Figure 8.—Sheet erosion has removed the topsoil and exposed the rocky subsurface. USDA Forest Service photo by Curtis Kvamme.



Figure 9.—Soil ring and associated tools for determining bulk density. USDA Forest Service photo by Will Rumpf.

Step 3: Assess the Plant Community

Observations of current vegetation on log landings and the surrounding areas are important for developing objectives for plant community enhancement.

Immediately following the harvest operation, log landings have little or no vegetation, but the adjacent areas are likely representative of the plant community prior to harvest and will provide a seed source for reestablishing plant communities during log landing recovery. Nearby log landings from past harvests may be used as examples of the recovery and development of the plant community over time; however, the type of harvest and approach used for processing and loading may result in log landings with different characteristics.

Soil Degradation and Invasive Plants

The degree of soil degradation and competition from invasive plants are two key challenges to the recovery of the native plant community. Severe compaction can inhibit the establishment of plants, reduce their growth after germination, and potentially impede their survival and reproductive capacity. Similarly, thick mulch layers reduce bare mineral soil exposure, limiting germination and growth.

A lack of native plant establishment and growth on log landings is often the first reason to implement a pollinator habitat enrichment project. A second motivating factor is an abundance of invasive plants. Invasive plants are often very competitive in disturbed environments and thrive in the open forest conditions and high light levels of log landings. Invasive plants can suppress native plants, alter the seed bank, and reduce the long-term success of establishing pollinator habitat. Invasive plants can also alter pollinator communities by attracting and favoring the non-native bee species that forage on them. Invasive plants may further alter the quality of the bee diet and disrupt bee foraging activity (Drossart et al. 2017). While some bee species are generalists and can forage on invasive plants, specialists require certain native species and can be directly impacted by shifts in plant composition.

Ways to Assess the Plant Community

- **Develop standard vegetation monitoring frameworks—**Standard vegetation monitoring frameworks often exist for specific forests or regions. The most appropriate monitoring protocol may depend on the specific conditions or objectives and the level of botanical expertise available. Common vegetation monitoring methods include walking transects, line transects, or systematic sampling of vegetation quadrats. These methods commonly include recording vegetation cover by species, genus, or functional group to gain information on the amount of vegetation of different types.

  These sampling protocols can be tailored for specific objectives. For example, focusing on key species of interest, such as plant species of known importance to pollinators or common invasive species, can be useful for generating targeted information and reducing the need for advanced botanical knowledge. When considering pollinator habitat, including a measure

of the abundance of flowering plants by species may be useful. Additionally, applications for plant identification (such as iNaturalist and PlantNet) are useful for identifying species in flower, especially to genus.

- **Evaluate the areas adjacent to log landings—**Vegetation monitoring can provide detailed information on the plant communities adjacent to log landings. Areas adjacent to new log landings usually represent the condition of the log landing pre-harvest and provide insight into the plant species that may have propagules within the soil. But if past land management practices have deviated from historical conditions, the surrounding vegetation may be largely devoid of the ground flora that was once predominate. For example, regions that were once open, fire-driven woodlands and savannas may have densified and lost their diverse and abundant ground flora due to the removal of frequent surface fire (Pile Knapp et al. 2024). High deer populations and overgrazing also can have long-term impacts on plant communities (Sabo et al. 2017). Ecological knowledge of former vegetation conditions is needed to identify and reintroduce plant species that grew in these former ecosystems, especially where restoration is the objective.

  Log landings that have been used repeatedly may no longer have the same plants in the seed bank as adjacent areas and may have residual soil disturbance from previous use. However, seed dispersal into the log landing post-harvest will mostly come from areas immediately adjacent to the landing, including forest roads and skid trails, or directly from the harvesting equipment. Even without detailed vegetation sampling, understanding the general forest type and its associated plant community is useful for developing expectations for plant community recovery on log landings.

- **Evaluate log landings from past harvests—**Log landings used in past harvests provide examples of recovery over time. When planning, it is most useful to compare landings with similar harvest and processing approaches, soil conditions, forest types, and plant communities. With the assumption of similar starting conditions, past log landings that cover a range of years since harvest offer insights into the trajectory of the plant community over time. Vegetation monitoring of these past log landings can indicate whether plant communities will likely provide improved habitat over time or the degree or rate at which invasive plants may begin to dominate. It may be particularly helpful to identify recent (within 1 to 2 years) log landings to determine the early establishment success of native plants. Native plants that have established rapidly on these landings are solid additions to enrichment seed mixes.

- **Identify invasive plants—**Invasive plant species are likely already established within the forest adjacent to the log landing. If invasive plants are abundant in the forest or were present on the site before harvest, they will likely be abundant in the log landing after harvest.

Harvesting equipment may also introduce invasive plants, so log landings, skid trails, and forest roads are vulnerable to invasive plants even if populations in the adjacent area are low. Invasive plants may quickly monopolize resources required by native plants and can homogenize the plant community of a log landing. Being familiar with the invasive species likely to present challenges and the local growing hotspots can help anticipate steps needed to mitigate their harm.

- **Identify current soil mitigation practices—**Some plant species seeded into log landings to prevent soil movement (e.g., annual rye) may have inhibitory effects (allelopathy) on the establishment and growth of other species. Monitoring plant community responses in the seasons following cover crop seeding can help to determine whether long-term objectives are being met beyond short-term soil erosion mitigation. Potential solutions include using non-allelopathic species or applying a native pollinator seed mix with a native grass component upon close out of the harvest.

- **Consider changing environmental conditions likely to impact the area and adaptation actions—**Changes in climate are altering growing conditions and will likely have impacts on current and reference plant communities. Forests and grasslands in the United States will experience warmer temperatures, and many areas will have changes in patterns and durations of drought, precipitation, growing season length, and more. Learning about potential and recorded changes for the project area can guide adaptation actions that include species selection, genetic selection, number of species in a seed mix, and mix of perennial and annual plants to meet goals over time. For an example of how a project in the western United States has used climate information to inform native plant revegetation and pollinator habitat planning, see the U.S. Department of Transportation, Federal Highway Administration (2017) report on roadside revegetation, section 3.3.1.

Step 4: Define Enhancement Objectives and Set Timelines

The following questions can guide the development of desired outcomes and timelines for a log landing enrichment project.

- **What are indicators of success?** Success indicators can be simple and limited to one or a few metrics or cover a broad suite of ecological and social metrics. Indicators could include increased floral diversity and abundance, floral availability throughout the growing season, increased abundance and diversity of native pollinators, reduced soil compaction, and increased carbon storage and water infiltration. Other possible indicators of success can include human dimensions of landing enrichment, such as landing beautification, public outreach and education, or increased recreational use.

Identifying success indicators and prioritizing their importance before treatments are implemented will help to focus the project on what is achievable and measurable and allow practitioners to explain the purpose of the project, evaluate success, and determine when adaptation is necessary.

- **How will success indicators be measured and evaluated?** Some measures of success may be more complicated or require greater skill than what is achievable or available. However, some measures of success can be surrogates for others. For example, observing an increase in the abundance and diversity of pollinator-preferred plants (which are fairly easy to identify) may suggest an increase in the abundance and diversity of native pollinators (which are more difficult to identify and often require observers to have specialized skills) and also that soil compaction levels are not limiting root growth. Measures of public outreach or recreational use could include informational kiosks with ways to record visitation metrics.

- **What is the timeline for success?** Setting timelines for evaluation helps decision making as the project moves forward. For example, a goal of abundant and diverse floral log landings in the first year is likely unachievable. A 3-year period is more reasonable to determine a response from the enrichment treatments, but after 10 years the enhanced plant community might not differ from the natural plant successional patterns following disturbance, especially for plant abundance. Focusing on desirable native species abundance may be more useful.

  A timeline can also provide guidance on species to keep or remove from a seed mix because it will show which species met the objective for establishment. For example, identifying seeded plant species that successfully established and flowered by the third growing season and those that should have but did not can help fine-tune seed mixes for future landings. Timelines also help practitioners prioritize monitoring programs and facilitate the adaptive management cycle.

- **What resources are needed to achieve success?** Whether the project involves enhancing one or a few log landings or a large compartment of landings, knowing the resources needed to achieve success prior to initiating a project is important. For example, consulting a soil scientist would be beneficial if soil compaction is a concern, and other specialists can provide valuable expertise for other success metrics. Identifying operational needs is also important. Can work be done in-house or will it need to be contracted? If contracted, how will the costs be covered?

- **How will monitoring inform adaptive management?** Determining success indicators, setting clear timelines, and monitoring outcomes allow practitioners to alter enhancement projects midstream or apply to future landings based on lessons learned. Having some level of replication (i.e., a few landings) of the same management regime allows for understanding results that can be adjusted for the next set of replicated log landing enhancement projects.

IMPLEMENTING A LOG LANDING ENRICHMENT PROJECT

This section provides guidance on implementing a native bee enrichment project on log landings after site conditions have been assessed and objectives and timelines have been set.

Improving Soil Conditions for Native Bees and Plant Establishment

Tillage and Subsoiling

If initial monitoring finds that a log landing's soil is compressed near or past the compaction threshold of 1.4 g/cm^3 (0.051 lbs/in.^{3}) beyond which plant roots cannot penetrate the soil, the following strategies can be used to mitigate the effects.

- **Tillage—**Tillage is a soil decompaction strategy that uses mechanical disturbance to break up soil and increase porosity. The term tillage may suggest rototillers such as those used in gardening or agricultural operations, but it is different. Rototilling mixes the soil, which disrupts the soil's natural structure and may increase density below the tilling. Tillage in a soil remediation context breaks up compacted soils and avoids mixing between horizons or depths.

- **Subsoiling—**Subsoiling is a less invasive method of tillage. Subsoilers use several long knife-like tines (18 to 40 in.) to cut through the soil, lifting and breaking it deep down. Subsoilers can be mounted on a variety of machines, including skid steers, tractors, and excavators, but they are most effective when used on equipment with booms that can reach out and rip without driving directly on the soil. Subsoiling is effective in post-harvest soil remediation (Case Study 3). By lifting and breaking up the soil, subsoiling increases water infiltration and speeds up the natural processes that help soil rebound from compaction. The U.S. Department of Agriculture, Forest Service developed and patented a subsoiling grapple rake for silvicultural prescriptions that combines brush and slash piling with subsoiling to reduce compaction (Monk 2009). Using equipment that can do two things with the same excavator head reduces on-site costs.

Case Study 3
PHiLL Project: Using a Subsoiler to Reduce Soil Compaction in Log Landings

Soils differed in their degree of compaction across the 15 log landings that were experimentally treated in the PHiLL project. Prior to treatment, all landings were assessed for compaction by removing a small volume of soil with a metal ring inserted in the soil at depths of 0 to 4 inches, 4 to 8 inches, and 8 to 12 inches (Fig. 10). The soil was bagged, coarse materials were removed, soil was dried, and the fine-earth fraction (soil passing through a #10 sieve) was weighed. All landings showed some level of compaction compared to soil in the undisturbed forest adjacent to the log landing.

Finer textured soils on the Hoosier National Forest (Indiana) and on the Shawnee National Forest (Illinois) had soil bulk densities that exceeded 1.4 g/cm^3 (0.051 lbs/in.^{3}), indicating that they were severely compacted. Rocky soils, like those occurring on the Mark Twain National Forest (Missouri) were less compacted, likely because the coarse fragments (rocks too large to pass through a #10 sieve) protected the soil from the compressive forces of the heavy machinery. To mitigate some of the compaction, the PHiLL project treated log



Figure 10.—Soil rings were hammered into the soil profile at different depths to assess the degree of compaction from the upper surface of the soil to 12 inches below the surface (A). Soil rings were carefully excavated, bagged, and labeled for further processing (B). USDA Forest Service photos by Lauren Pile Knapp.

landings with a subsoiler mounted to a skid steer. The tines on the subsoiler were spaced 2.5 feet apart and were pulled through the soil at a depth of 20 inches (Fig. 11). Results from the study suggest that subsoiling reduced soil compaction in the upper few inches of soil but that the compaction reduction was greatest when subsoiling was combined with biochar amendments (Rumpf 2024).

A



B



C



Figure 11.—Subsoiling to reduce compaction on log landings. A subsoiling rake was purchased for use on log landings to reduce compaction. The tines were 2.5 feet apart and could reach depths of 20 inches (A). Chad Menke (Hoosier National Forest) observes as the subsoiler, mounted on a skid steer, is pulled in reverse to avoid driving over the treated soil (B). John Kabrick (Northern Research Station) evaluates the performance of the subsoiler immediately following treatment (C). USDA Forest Service photos by Lauren Pile Knapp.

Although log landings may be flat and clear of aboveground obstacles, there are often belowground obstacles—rocky soils, stumps, and large roots—that make subsoiling difficult. Having skilled operators who can work around obstacles is important. Using boom-operated vehicles or rippers with fewer tines can improve the dexterity and effectiveness of equipment and avoid belowground obstacles.

Belowground subsoiling may affect ground-nesting forest bee species, an understudied topic. Tilling may destroy bee nests, depending on the depth of tillage, because the average minimum nest cell is 6.7 inches deep (Cane and Neff 2011, Harmon-Threatt and Chin 2016). Therefore,

use of repeated, deep tillage or subsoiling may have negative effects on ground-nesting bees. However, even for well-studied species common in agricultural settings, such as the squash bee (*Eucera pruinosa*), study results on the effects of tilling are mixed. Some studies report reduced nest success in tilled areas (Ullmann et al. 2016), while others indicate no difference in nest success and a preference for nesting in tilled areas with disturbed soil (Skidmore et al. 2019). It seems that subsoiling could lead to overall increases in ground-nesting bee abundance because reduced soil compaction and enhanced plant growth would improve bee habitat. Additional research can improve guidance on reducing soil compaction without adversely affecting soil-nesting bees.

Soil Scarification

Soil scarification can improve seed germination and reestablishment of vegetation. Generally done by hand or with a harrow, scarification is a form of surface tillage that exposes the mineral soil. The surface tillage increases water infiltration and allows new seeds to settle into and make direct contact with bare mineral soil to facilitate germination.

Slash and Mulch Removal

On sites where whole tree harvest has left significant residues, removing slash and mulch before subsoiling, adding biochar (see the next section), or seeding allows for natural rebounding of soil and reestablishment of vegetation. A skid steer, tractor with a bucket, or the subsoiling grappler rake can be used to carefully remove slash and mulch, with care taken not to scrape or mix the topsoil.

Biochar

Biochar as a Soil Amendment

Biochar is a material created by heating carbon-rich biomass feedstocks (e.g., harvest residue or slash; Fig. 12) in a low- or no-oxygen environment. This production process, known as pyrolysis, separates biomass components (e.g., water and gasses) and transforms the biomaterial into a durable form of carbon that can persist in soil for hundreds of years or more. Biochar characteristics are dependent upon the feedstock and temperature, but most biochar has high surface area, alkaline pH, and high nutrient exchange and water holding capacity. These properties, along with the ability to store carbon long term in soil, have made biochar a popular soil amendment for soil restoration (Case Study 4).



Figure 12.—Slash piles created during stand thinning operations. USDA Forest Service photo by Joanne Tirocke.

Case Study 4
PHiLL Project: Applying Biochar to Log Landings

Early conversations in the PHiLL project included whether adding biochar as a soil amendment in the experiment would improve plant establishment and growth, and subsequently, native bee habitat. Because mechanisms were not in place to produce biochar on-site and to reduce the variability of biochar product for experimental reasons, a softwood-derived biochar—a highly uniform product with a particle size that resembles sand—was purchased from a regional supplier (Wakefield Biochar, Columbia, MO, USA; Fig. 13a). The biochar was applied at a rate of 10 tons per acre and spread using a self-propelled fertilizer broadcaster that was rented locally (Fig. 13b). When treatments included both subsoiling and biochar, biochar was spread first, followed by subsoiling to increase the soil incorporation of the biochar.

Results from the study suggest that compaction was most reduced when biochar and subsoiling were combined. Biochar applications were associated with increases in potassium, magnesium, phosphorus, and total carbon and nitrogen (Rumpf 2024). Additionally, native bee nests were observed in areas treated with biochar within a year of treatment, and abundant ground-nesting bee species were collected on landings treated with biochar.

A



B



Figure 13.—Example of the biochar product used in the PHiLL project log landings (A). Chad Menke (Hoosier National Forest) spreads the biochar using a self-propelled fertilizer spreader that was rented locally (B). USDA Forest Service photos by Lauren Pile Knapp.

Current laboratory studies on the direct effects of biochar on insects have shown that a range of invertebrate and insect species may experience lethal effects, especially with direct exposure and high concentrations due to dehydration, potential interference with respiration, and heavy metal exposure that might be present in the biochar (Chen et al. 2022, Cook and Neto 2018, Hou et al. 2015, Salem et al. 2013). However, the use of biochar on compacted landings may benefit ground-nesting native bees by reducing compaction and promoting plant growth. More research can help guide field applications.



Figure 14.—Big box, flame-capped kiln created by Darren McAvoy (Utah State University). The kiln is double walled to conserve heat and make it easy to hand or equipment load. USDA Forest Service photo by Derek Pierson.

Biochar Production and Application

The following summaries of in-woods (or place-based) biochar production methods are described in detail in Wilson et al. (2024), which includes further information on loading, water needs, production data, and siting.

- **Hand and machine piles—**Biochar can be made in hand or machine burn piles. Piles are burned to optimize clean burning and biochar production by producing flaming combustion as quickly as possible to reduce smoldering. Piles that optimize biochar production are lit from the top to burn more of the particulates in the smoke. Heat transfers downward by radiation. At the end of the burn, glowing coals are quenched with water or raked out to preserve biochar. Details on appropriate fuels, building methods, heat optimization, and tending and quenching piles can be found in Wilson et al. (2024). See additional information on hand pile construction and burning here.

- **Flame-cap kilns—**A flame-cap kiln is a simple container that holds woody residues during burning (Fig. 14). The container does not require a bottom. Where the bottom is not enclosed, the edges in contact with the soil are sealed with additional soil so that all combustion comes from above. The size

and shape of the container can vary, but generally the width is greater than the height to facilitate air flow from the top. Woody residues are loaded into the container and lit on top. Once the initial material has burned down, additional material is added until the kiln is full of glowing coals. At this point, the coals are quenched with water and raked into the forest soil. Generally, one to two batches of biochar can be created in an 8-hour day, depending on fuel size and moisture content. Kilns are excellent tools to use with conservation crews at roadsides or on log landings because they are easy to assemble and use, are relatively inexpensive, and produce biochar that can be used on-site.

- **Air curtain burners**—Air curtain burners are insulated fireboxes on skids, wheels, or tracks with a blower to control airflow across the top of the firebox. The air curtain reduces emissions significantly when compared to open burning (Lee and Han 2017). Air curtain burners are loaded with an excavator, log loader, or other equipment. Some burners require batches of coals to be unloaded and quenched with water (e.g., BurnBoss®, Air Curtains Inc., Palm City, FL, USA); other types create biochar continuously (e.g., CharBoss®, Air Curtains, Inc; Fig. 15), and the coals are quenched as they exit the firebox. Air curtain burners can run as continuous processors for multiple shifts. Optimal locations for using air curtain burners are at roadsides, log landings, campgrounds, or near wildland-urban interface areas. Wilson et al. (2024) discusses tradeoffs between using flame-cap kilns versus air curtain burners.



Figure 15.—Andrew Bidwell (Lolo National Forest) lighting a CharBoss® (Air Curtains, Inc., Palm City, FL, USA). USDA Forest Service photo by Joanne Tirocke.

Biochar Application Methods

Biochar can be applied using a variety of methods. For example, a biochar spreader (Page-Dumroese et al. 2016) has been developed that is pulled behind a log forwarder. This spreader, which is a modified salt spreader, has clearance to travel over stumps and logs, can traverse slopes up to 35 percent, and has an adjustable spread distance and rate. This and other spreaders of similar size are appropriate for large area applications such as a thinned stand or skid trail.

Fertilizer or manure spreaders can also be used for large-scale applications. If the biochar is applied to disturbed soil (e.g., a log landing or mine site) with no intact organic horizons, the biochar can be mixed into the mineral soil with a grappler or excavator. When biochar is applied on the surface of an intact forest floor, it will naturally move through the organic horizon and into the mineral soil, but the rate that this happens is determined by biochar particle size and climatic regime.

For small-scale projects, biochar can be added to a seedling planting hole using a 5-gallon bucket. Biochar made in kilns or in conservation burn piles can be raked out and left in place. Larger quantities produced by air curtain burners can be used on-site or moved to a nearby location, usually within a watershed.

Biochar Application Rates

Biochar can be applied at a variety of rates. In general, biochar applied at rates between 1 and 10 tons per acre have been used on forest sites. The application rate depends on the type of biochar, soil properties, and project goals. Higher rates (5 to 60 tons per acre) of biochar are often used on contaminated sites. When biochar is added to a planting hole, it should not exceed 25 percent of the hole volume and is mixed with the mineral soil before filling in the hole.

Enhancing the Native Plant Community

Native Plant Selection and Establishment

Developing a native plant list can be a daunting task. Select species that have several favorable qualities: ability to establish across a range of site conditions and provide floral resources for pollinators, capacity to aggressively compete with invasive species, and availability for collection or purchase at reasonable cost (Case Study 5). Diverse native pollinator seed mixes are commercially available and may be suitable for establishing some key species on log landings, but they are often expensive and may contain species that will not be successful. Developing site- or forest-specific seed mixes based on experience may also be possible. Following are considerations for developing a native plant list:

- **Nativity—**Plants that are native to the ecosystem and region where the log landing is located are more likely to establish successfully. If possible, consider using local seed sources. Assisted population migration or assisted range expansion could be considered for matching

future climate scenarios and may need further evaluation for plant-pollinator interactions with a changing climate.

- **Pollinator suitability—**Evaluate each species in the plant mix for its use by pollinators (see App. 2 for resources).

- **Floral resource availability—**Consider species that provide resources in the early, mid, and late growing seasons, with multiple flowering species for each stage of the growing season.

- **Competitiveness—**Consider plants that can establish and compete with invasive plants or native ruderals that are not considered high-quality pollinator resources. It may be appropriate to include some native species that are good competitors, despite lower pollinator use, to reduce invasive species establishment.

- **Broad ecological amplitude—**Consider species that can establish and grow across a wide range of site conditions. These plants are more likely to be successful than those with a narrow range of optimum conditions or specific requirements. Considerations could include large native home ranges, adaptability to drought, and shade tolerance.

- **Rapid establishment and maturation—**Consider germination and establishment speed. Species that are slow to germinate or have strict germination requirements may be unlikely candidates for establishing pollinator habitat. Selecting plant species that are highly likely to flower within the first growing season will create pollinator habitat faster than plants that are slower to mature.

- **Seed or plant availability—**Many common plant species that fit the above requirements are often available by seed, and a local seed supplier can be helpful in developing a plant list. In addition, identifying and collecting seed not available on the market may be an option. See the following section on selecting plant materials for information on availability and sourcing.

- **Cost—**Prices for individual plants vary by species and size. For seeded species, the cost depends on the rate at which seeds are applied. When planning for enrichment and budgeting seeding costs, there is often a balance to be struck between seeding rates and the size of the seeded area.

Case Study 5
PHiLL Project: Identifying the Right Seed

Choosing a native seed mix was an early and important step in developing the PHiLL project. A team worked through which plant species to include based on the characteristics described in this section. The team developed a diverse seed mix (28 forbs and 4 grasses) for the purpose of evaluating the establishment success of different plant species in the project's log landings. Species that were deemed successful would be moved to seed mixes for planting on future landings. The goal was to develop a seed mix that would establish quickly (within 3 years), provide floral resources throughout the growing season, be obtained easily, and be economical for scaling up.

By year 3 of the PHiLL project, only a few plant species in the seed mix performed well—meaning that they were abundant and flowering across most of the experimental landings within the first few years of seeding. Successful flowering species included coreopsis species, black-eyed Susan (*Rudbeckia hirta*), bergamot (*Monarda fistulosa*), slender mountain mint (*Pycnanthemum tenuifolium*), partridge pea (*Chamaecrista fasciculata*), narrow-leaved sunflower (*Helianthus angustifolius*), and showy tickseed (*Bidens aristosa*) (Fig. 16).

Other species in the seed mix were slow to establish and flower, and several were not observed at any of the landings. For example, foxglove beardtongue (*Penstemon digitalis*) is generally weedy in the region, but it was rarely observed on the landings. Successful grasses included little bluestem (*Schizachyrium scoparium*) and river oats (*Chasmanthium latifolium*), both of which performed well and gained each year following initial seeding.

A key lesson learned was that selecting an economical seed mix that could be broadly applied requires an iterative and deductive process to select bee-beneficial plant species that establish rapidly and thrive in a range of ecological conditions.

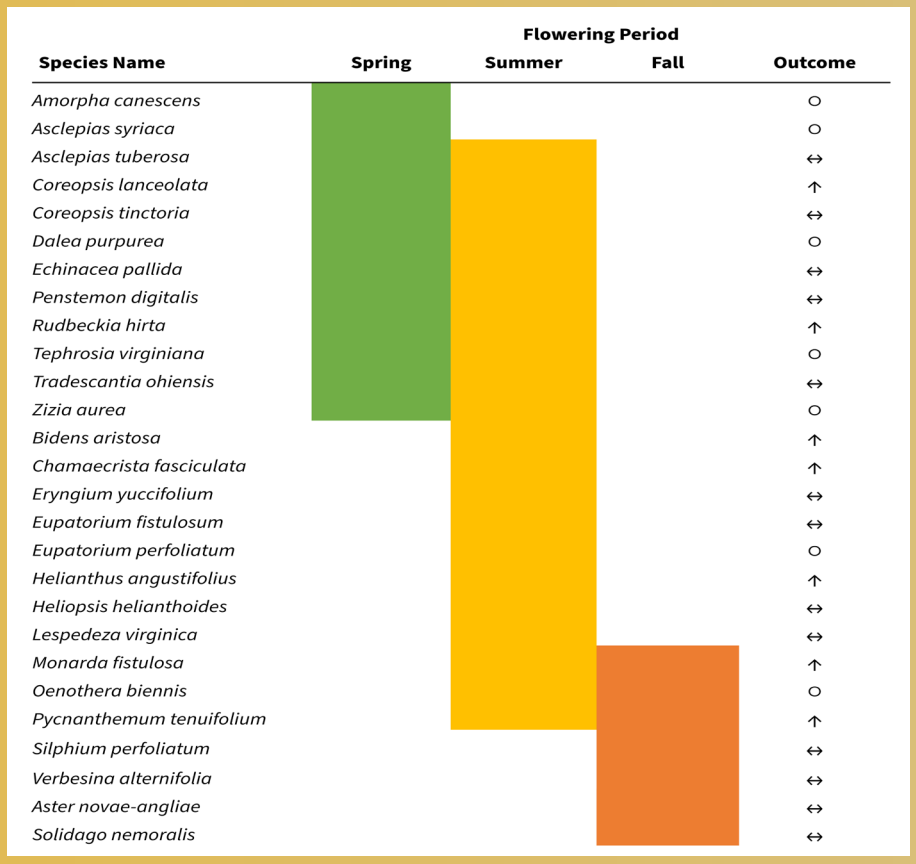


Figure 16.—Species selected for the PHiLL project seed mix, their flowering period, and outcome after 3 years of monitoring across 15 log landings located in Indiana, Illinois, and Missouri. An abundant ranking (↑) indicates that the seeded plant occurred on many of the treated landings and was often numerous where it occurred. An occasional ranking (↔) indicates that the seeded plant occurred on several landings and often as individuals or small clumps. A rare or absent ranking (○) indicates that the seeded plant occurred rarely on one or a small number of landings as an individual or was not observed.

Selecting Plant Materials

After developing the plant list, the next step is to identify the best propagation method and plant material source to increase the probability of enrichment success. While seed mixes are commonly used for restoring native plant communities, other types of plant materials that may be available include vegetative propagation from roots or cuttings as well as nursery-grown plants such as seedlings or plugs. In addition, some species readily produce and establish from seed, whereas others do not reliably produce seed crops or readily establish by seed, necessitating the use of other plant materials for propagation. This discussion covers herbaceous plants, but cuttings may also be readily used for some trees and shrubs. Following are considerations for selecting, sourcing, and applying plant materials.

- **Plants—**Plants grown in greenhouse or agricultural settings are typically used when direct seeding of a species results in limited success. The outdoor germination rates of some species can be low. Starting these species indoors and then outplanting can increase success.

- **Establishment method—**Some species and conditions may require seedling plugs or vegetative means of propagation other than seed. Adaptive management is encouraged to learn which species are reliably successful at establishing from seed.

- **Vegetative structures—**Some species (e.g., milkweeds [*Asclepias* spp.]) are perennial and can be propagated by cuttings or dividing the roots. This method allows plants to establish more quickly and is often preferred for plants that are difficult to establish from seed.

- **Seeds—**Seeds can be purchased from local native seed nurseries or collected in the wild. Direct seeding is often the most cost-effective method of establishing plants across large areas, particularly forbs and grasses.

- **Seeding rates/planting density—**Local native seed suppliers can be helpful for determining seeding rates and proportions of pure live seed by weight for the selected seed mix. Typically, seeding rates between 8 and 12 pounds per acre are recommended.

- **Application period—**Seeding is recommended from late fall to the early growing season and could occur during the dormant season following closeout of a timber sale.

- **Spreading seed—**Seed can be spread by hand or using commercially available seeders. Seed can be mixed with cat litter, vermiculite, or other products to allow for good seed dispersal. Seed can be lightly topped with weed-free straw to reduce movement and predation by birds.

Practical Considerations for Implementing Enhanced Log Landings

The practical decisions required to implement log landing enrichments on the ground are just as important as the ecological information that underpins these activities. Although some practical considerations vary based on land ownership and by region, managers who have implemented the PHiLL project and similar enhancement efforts have learned lessons that can help future projects succeed (Case Study 6). These include decisions around timing, contracting, and managing visitation of enhancement-treated sites.

Timing

The optimal time for enhancement activities to occur is soon after the landing is no longer used by loggers because the landing has not yet been naturally revegetated by species that may be undesirable for pollinator habitat. In forests impacted by invasive plant species, timing is an even greater concern because established invasive plants may spread to the landing and be even more challenging, time consuming, and expensive to eradicate. The following considerations can help practitioners time enhancement activities.

- **Pre-treatment scouting—**Consider scouting log landings before they are closed out to assess remediation needs. Early scouting and planning based on observed conditions facilitate more rapid treatment when landings close. For example, log landings with many remaining stumps may be impractical for enrichment operations that require machinery. However, if the soil surface has exposed mineral soil and is not compacted, then seeding could occur immediately after the landing is closed out.

- **Planning based on payment units—**If possible, enter a payment unit or harvested area shortly after it is completed, when plants have not yet colonized the landing, rather than waiting until after the entire sale is closed, which may be years after the landing was last used. Planning enhancement activities around payment units is advantageous because these units are typically closed at the end of each season.

- **Mulch management—**To inhibit revegetation and prolong the treatment window after the landing closes, keep mulch on the log landing until the end of the growing season (late summer or early fall). Seeding can then occur in the winter or early spring. Avoid leaving mulch over the winter because soils may be too wet in the spring for equipment to operate on the landing. This timing of enhancement activities inhibits revegetation until the spring, when soil and plant enrichment activities can occur.

Case Study 6
Moving Beyond PHiLL: The Mark Twain National Forest

Based on results from the PHiLL project, in 2024 the Mark Twain National Forest (Missouri) began implementing native bee enrichment projects on 12 landings of the Phantom and Avenger timber sales on the Eleven Point Ranger District. The landings were selected within a larger shortleaf pine woodland restoration project. On these landings, soil compaction was not an issue, but pine mulch and logging slash needed to be removed to expose bare mineral soil for the seedbed. Sites were prepared using a rented power rake attachment on a skid steer driven by an equipment operator (Fig. 17). Using the successful species identified through the PHiLL project, district staff hand seeded the landings at a rate of 10 pounds per acre with cat litter as a carrier. Following seeding, a roller on an ATV ensured good soil-seed contact (Fig. 18).



Figure 17.— Implementation of pollinator enrichment on log landings of the Mark Twain National Forest, Eleven Point Ranger District. A grapple removes large debris from the log landing (A). A power rake attachment on a skid steer helps expose bare mineral soil to prepare the seed bed (B). The final condition of the log landing, ready to accept the native seed mix (C). USDA Forest Service photos by Corey Large.

Mark Twain district staff shared the following lessons learned:

- Prioritizing landings based on condition minimizes time and cost. Closed timber sale areas may already have revegetated and require additional preparation. Newer landings with minimal debris and stumps require less preparation.
- Deep layers of mulch are difficult to deal with and pile up quickly. Heavy mulch layers and large debris can result in wet sites. Clearing sites in late summer or early fall also allows for more days during the dormant season to power rake and seed.
- Hand seeding may work better than a handheld broadcast seeder. Other types of broadcast seeders may produce better results.
- Visuals are important. Signs that explain log landing projects and sites that are free of debris piles improve perception in areas used by the public.

A



B



C



Figure 18.— Seeding a log landing on the Mark Twain National Forest, Eleven Point Ranger District. Forester Corey Large spreads the native seed mix (A) and Forester Scot Robinson ensures good soil-seed contact with an ATV-roller (B). Example of a seeded log landing (C). USDA Forest Service photos by Scot Robinson (A) and Corey Large (B, C).

Contracting

Identifying the location and number of log landings to enhance is an important step to take before contracting because the scope of enhancement activities will influence, and possibly determine, the contracting options that are most feasible and appropriate. After making these planning decisions, talk with your contracting officer early and often about whether the planned enhancement activities can be accomplished with in-house staff and resources or whether a contractor is required.

Discussions with the contracting officer are informed by on-the-ground scouting (see the preceding section on timing) to determine whether log landing enrichment will require activities beyond traditional log landing closeout procedures. Any extra activities need to be specified when contracting, such as an application of a native seed mix rather than a standard erosion control application of annual wheat or rye. A stewardship contract may allow greater flexibility in log landing rehabilitation and native seed enrichment than a traditional timber contract.

Generally, smaller-scale operations are easier to complete in-house or with contractors on an ad-hoc basis, whereas larger efforts involving multiple timber sales may require consistent contractor support. For more flexibility for experimenting with what works for a particular site condition and forest type, it may be easiest to start small with in-house resources, ad-hoc contractor support, or both.

Managing Visitation and Use

Log landings on public lands are often used by recreationists for parking, camping, and other activities, but use of enhanced landings, particularly vehicle use, may compromise soil and plant community rehabilitation efforts. To protect enhanced landings from unwanted visitation, consider creating a berm using mulch or debris to prevent vehicles from entering the landing. Another protective measure could be to post interpretive materials that explain the project and encourage visitors to stay off the landing. The signage could also provide information about alternative parking locations or campsites.

MONITORING AND ADAPTIVE MANAGEMENT OF A LOG LANDING ENRICHMENT PROJECT

Identifying Monitoring Objectives and Determining Intensity, Frequency, and Expertise

This section provides guidance on monitoring objectives, protocols, and the level of expertise required for implementing a native bee enrichment project on log landings.

Soil Monitoring

Soil monitoring can be conducted using the Forest Soil Disturbance Monitoring Protocol (FSDMP; Page-Dumroese et al. 2009a, 2009b) to assess soil disturbance pre- and post-harvest. Generally, soil monitoring is conducted 1 to 2 years post-harvest, but monitoring can be adjusted based on enhancement timing. During each sample time, the compaction, soil structure, organic horizon depth, rooting depth, and so on can be assessed either at fixed locations or along random transects. The FSDMP provides data that describe surface soil conditions that affect site sustainability and hydrologic function, and the soil monitoring data can be linked to individual plant growth or soil cover. Other soil functional data required to meet project objectives (e.g., organic matter, porosity, or surface crusts) can be collected during the FSDMP monitoring.

Plant Monitoring

Where available, a standard vegetation monitoring framework can be adapted to improve pollinator habitat on enhanced log landings. The monitoring protocol may be adjusted in frequency or intensity depending on time since harvest, the condition of present vegetation, and the objectives and timelines set during project planning. However, monitoring is recommended throughout the growing season (spring, summer, early fall) and on multiple landings to account for variation in plant responses over time and space.

Observations

At the most basic level, observing which plants are flowering and their abundance throughout the growing season is important to determine whether enhancement measures have been successful. These observations can include walking surveys and permanent photo points to identify flowering plant cover across the landing. Plant monitoring can be designed to target responses of species included in the seed mix and those not seeded. The same procedure can be repeated throughout the flowering season (spring, summer, early fall) and annually following the timeline determined during planning. This approach allows for adaptation at the log landing and at future landings.

Transects and Sampling Points

Transects with sampling points work well for more detailed vegetation monitoring on log landings (Figs. 19 and 20). Setting up several permanent transects helps account for differences in microconditions across the landing and over time. For example, soil compaction tends to be concentrated in the center of the landing and leading out to the road where logs are transported to mills. Sampling transects across the landing could account for any variation in compaction.



Figure 19.—Sloane Scott and Alisen Chapman (University of Missouri) record transect sampling data on a log landing in the Hoosier National Forest.



Figure 20.—A group collects data on the plant community within a sampling frame.

The transect monitoring method uses permanent monuments at each transect end. During sampling, a measuring tape is extended along the transect, and sampling frames are placed on one side of the transect. Data on the plant community are recorded within the sampling frames, and the other side of the transect allows for foot traffic without disturbing the vegetation. Sampling frames can be placed at regular intervals along the transect length to account for changing conditions (Fig. 21). Data that can be recorded include the percent coverage by species or genera, rocks, leaf litter, mulch, or wood (defined as any branches, logs or stumps greater than 1 inch in diameter that are potentially usable by wood-nesting bees) and the percent coverage of bare ground and standing water (often attributed to compaction). It is also important to collect data on which species are flowering to capture available floral resources for native bees and on coverage of pithy stemmed species, an indicator of nesting resources.

Plant Identification

Although plant identification apps are helpful, not all plants are easily identifiable in the field. Field plant presses can be used to bring samples to the office for further identification, or a camera with a white board and marker can make digital records of unknown plants for later identification. Photos that highlight structural details and with a ruler in the frame are most helpful for identification and monitoring.

A



B



Figure 21.—Sampling frame (A) and demonstration of how to record data using a frame (B). USDA Forest Service photos by Lauren Pile Knapp.

Bee Abundance and Diversity Monitoring

The method used for bee monitoring depends on the objectives and timelines identified during planning, which sets out the resolution of data needed (see App. 2 for resources on bee monitoring methods and protocols).

Transect Counts

In a transect count, an observer counts the number of bees along a linear transect to generate an index of bee abundance that can be compared among sites or before and after management to gauge success. Training may be necessary to ensure that observers can distinguish between bees and other insects like wasps or flies and, ideally, among various types of bees (e.g., domestic honeybees, native bumblebees, sweat bees [*Agapostemon* spp.]). Species-level identification is not possible with visual surveys, making them unsuitable for generating actual estimates of species richness or abundance of individual species.

Bee Capture

A more involved but scientifically valuable method involves capturing bees and either inspecting live specimens in the field, which for trained observers works for some large-bodied species like bumblebees, or more commonly, lethal collection for microscopic inspection in the laboratory. The latter method yields the most data but is laborious and requires advanced training or securing the services of a reputable taxonomist. Due to the high level of skill needed to identify bees to species, relatively few people are suitably trained, and thus most of them have backlogs of specimens. A general cost estimate as of this writing is $10 per specimen or $70 per hour. Lethal collection does not diminish bee populations because a relatively small proportion of individuals of any given species is captured.



Figure 22.—Aliza Fassler (University of Massachusetts-Amherst) teaches Jason Isbell (Hoosier National Forest) the standardized netting protocol. USDA Forest Service photo by Lauren Pile Knapp.

Two principal methods are used to capture bees for monitoring: standardized netting and passive trapping (e.g., pan traps, vane traps, or Malaise traps). For standardized netting, an observer traverses a fixed area for a set

period and collects all bees they see in the area (Fig. 22). Another type of netting, opportunistic netting, is not standardized by area or time but is directed toward an area or plant species of interest. Opportunistic netting is not suitable for generating standardized abundance estimates for comparing among sites or treatments; however, it can be used to generally characterize bee communities in an area of interest, or more importantly, to track bee-plant relationships provided the plant is also recorded.

Bee bowls, a type of pan trap, provide estimates of bee abundance and diversity in a sampled area. Common and easy to use, bee bowls consist of white, fluorescent blue, and yellow painted (UV visible) soufflé cups (SOLO® brand, 3.25 ounce) filled three-quarters with a mixture of water and Dawn® dish soap. Bees are attracted to the bright colors of the bee bowl, fall into the soapy water, and are unable to escape because the soap reduces the surface tension of the water. Sets of bowls are laid out in transects or arrays. Bowls are elevated or vegetation is pressed down to ensure that the bowls are visible from a short distance. Like netting, bowls and other traps are deployed for a standardized period and under ideal conditions. For example, sampling could be conducted for 24 hours on clear, dry days with low wind and temperatures above 60 °F (15.6 °C).

Other passive traps, such as vane traps and Malaise traps, can also be used to monitor bees; however, bee bowls can be dispersed across an area of interest and potentially yield a more accurate reflection of the influence of local conditions.

Bee bowls and other types of traps are often used in combination with netting because different methods catch different species of bees. Each sampling method has its pros and cons, and the choice of method needs to be guided by enhancement objectives—to increase bee abundance, expand diversity, support rare species, and so on. Consulting researchers at federal agencies (e.g., U.S. Department of Agriculture and U.S. Geological Survey), local universities, or extension programs may also help in selecting an appropriate monitoring method. For all methods, careful specimen labeling and proper storage procedures are essential.

Captured bees require processing in preparation for identification and, ultimately, for transfer to a museum collection where they can contribute to future research efforts that inform bee conservation. To prepare bees, the observer washes away any materials (e.g., pollen, ethanol, and so on) from the bee's body that may obscure features needed for identification. Specimens are then dried, which makes their hair patterns visible and aids identification; pinned; and labeled with the location, date, and method of collection, the name of the collector, and the plant species the bee was pollinating. See Appendixes 2 and 3 for resources and guidance on sampling protocols and specimen care.

Forest Management for Native Bees Beyond Log Landings

Beyond enhancing log landings, active forest management has an important role in sustaining and promoting habitat for native bees. Managing for these species has numerous benefits. Pollination is necessary for the persistence of flowering plants, including rare species that are unable to produce viable seeds in the absence of effective pollination. Plants that have been pollinated and produce fruit or seeds provide resources such as soft mast for birds and other wildlife species that consume fruit to prepare for migration and hibernation. These pollinated plants store carbon, provide shade, and produce natural resources for people, such as timber and food.

The simplification of forest ecosystems that has occurred over the past centuries has decreased populations of plant species and over time has reduced the numbers of some native bee species to rare and endangered levels. Management to support native bees therefore requires the enhancement of native flora, which in turn augments native biodiversity and supports other pollinator species—butterflies, wasps, and beetles—that provide essential ecosystem functions and services.

In general, management practices that increase the abundance of herbaceous ground flora benefit pollinators, and management approaches used for other objectives can be compatible with enhancing pollinator habitat. Open forest ecosystems such as woodlands and savannas are often appreciated for their aesthetic value, high diversity of plant species, and habitat value for wildlife. Recognizing that these habitats also provide quality habitat for bees and other pollinators may provide greater motivation for restoration and maintenance of open forest ecosystems across the landscape. In addition, maintaining landscape variability in structure and age distribution is important for providing heterogeneous habitat, including early successional conditions. For example, in addition to managing open forest habitat, regenerating even-aged forests provides early successional habitat for 5 to 10 years and may be necessary for replacing maturing trees in some forest types. Considering the availability of various habitat conditions across the landscape can inform harvesting schedules and other management decisions.

This log landings enrichment guide for natural resource managers serves as a first step to having conversations about actively promoting pollinator habitat to augment native biodiversity. Managers interested in promoting pollinator habitat outside of log landings may also consider implementing one or more of the following ideas:

- Restoring open forest habitats, such as savannas and woodlands, where appropriate and based on historical conditions.

- Maintaining heterogeneous forest landscapes that provide habitats for bees associated with both closed-canopy and open-canopy forests.

- Expanding pollinator habitat from log landings to decommissioned roads and skid trails, which can provide within-stand connectivity between enriched log landings.

- Reducing excessive woody residue volumes by using non-merchantable timber and place-based biochar production methods to enhance pollinator habitat in areas outside of log landings. Biochar can restore soil chemical, physical, and biological properties for greater plant enrichment.

- Using prescribed fire as a restoration technique, as appropriate, to benefit the wild bee community.

- Managing wildlife openings for pollinators, such as seeding beneficial pollinator plants and maintaining open forest structure.

- Protecting populations of plants that specialist bees rely on as food sources and plants used as hosts by caterpillars.

- Increasing awareness of native bees and other pollinators. Although several species of native bees are in well-documented population decline, population trends for most species remain unknown. Observations of various pollinators uploaded to platforms such as iNaturalist can provide important occurrence data.

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ENGLISH AND METRIC EQUIVALENTS

When you know	Multiply by	To convert to
English		**Metric**
inches	2.54	cm (centimeters)
feet	0.3048	m (meters)
miles	1.60934	km (kilometers)
acres	0.40486	ha (hectares)
lbs/in.^{3} (pounds/cubic inch)	0.0361	g/cm^3 (grams/cubic centimeters)
lbs/acre (pounds/acre)	1.12	kg/ha (kilograms/hectare)
tons/acre	2.24	Mg/ha (megagrams/hectare)
Metric		**English**
cm (centimeters)	0.393701	inches
m (meters)	3.28084	feet
km (kilometers)	0.621371	miles
ha (hectares)	2.47105	acres
g/cm^3 (grams/cubic centimeters)	27.6799	lbs/in.^{3} (pounds/cubic inch)
kg/ha (kilograms/hectare)	0.8922	lbs/acre (pounds/acre)
Mg/ha (megagrams/hectare)	0.446	tons/acre

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APPENDIX 1

Enriching Log Landings for Pollinators Worksheet

1.0 LOG LANDING POLLINATOR ENRICHMENT PRESCRIPTION

1A. MANAGEMENT DECISION DOCUMENT _____

1B. PROJECT NAME _____

1C. PURCHASE UNIT _____ **1D. COMP/STAND** _____ **1E. SALE UNIT ID** _____

2.0 LOG LANDING HARVEST INFORMATION

2A. DISTRICT _____ **2B. LOG LANDING COORDINATES** _____ **2C. HARVEST AREA ACRES** _____ **2D. HARVEST PERIOD** _____

2E. CLOSEOUT DATE _____ **2F. SPECIES COMPOSITION** _____ **2G. SILVICULTURAL PRESCRIPTION**

3.0 LOG LANDING DESCRIPTION

3.1 SOIL SERIES _____ **3.2 PRIMARY ELTP** _____

3.3 LANDING AREA (acres) _____

3.4 MATRIX LAND COVER TYPE

- DEVELOPED ☐
- AG - PASTURE ☐
- AG - CROPLAND ☐
- SHRUBLAND ☐
- GRASSLAND ☐
- FOREST - OPEN ☐
- FOREST - CLOSED ☐
- WETLAND ☐
- BARREN ☐

3.5 SOIL TEXTURE

- SILT LOAM, SILTY CLAY LOAM, SILTY CLAY, CLAY ☐
- LOAM, CLAY LOAM ☐
- SANDY LOAM, SANDY CLAY LOAM, SANDY CLAY ☐
- LOAMY SAND, SAND ☐

3.6 COMPACTION LEVEL

- LOW ☐
- MEDIUM ☐
- HIGH (requires mitigation) ☐

3.7 ADDITIONAL REMARKS

3.8 POTENTIAL FOR NATIVE PLANT ESTABLISHMENT

LOW ☐ MODERATE ☐ HIGH ☐

3.9 POTENTIAL FOR INVASIVE PLANT IMPACT

LOW ☐ MODERATE ☐ HIGH ☐

3.10 SIGNIFICANT RESIDUAL MULCH/SLASH

LOW ☐ MODERATE ☐ HIGH ☐

4.0 DESIRED CONDITION

4.1 SHORT-TERM OBJECTIVES

4.2 LONG-TERM OBJECTIVES

4.3 DESIGN CRITERIA AND MITIGATION MEASURES

4.4 SEED MIX COMPONENTS

EARLY-SEASON FLOWERING	MIDSEASON FLOWERING	LATE-SEASON FLOWERING
1	1	1
2	2	2
3	3	3
4	4	4
5	5	5
6	6	6
7	7	7
8	8	8
9	9	9
10	10	10

GRAMINOID

1

2

3

4

5

4.5 OTHER REMARKS

4.6 CONSIDERATIONS FOR NESTING RESOURCES

Enriching Log Landings for Pollinators Worksheet (continued)

5.0 TREATMENTS

5.1 SEASON/YEAR	5.2 DESCRIPTION	5.3 PRESCRIPTION

6.0 MAP (place image below)

Prepared by _____ Title _____ Date _____

Prepared by _____ Title _____ Date _____

Prepared by _____ Title _____ Date _____

APPENDIX 2

Selected Resources for Pollinator Enrichment Projects

Topic	Resource	Type	Description/developer
Pollinator plants	Pollinator-Friendly Native Plant Lists	Online	Lists of plants used as food sources for adult pollinators, host plants for caterpillars, and plants that provide nesting habitat for wild bees for each major U.S. region. Developed by the Xerces Society for Invertebrate Conservation.
Pollinator plants	Native Plant, Seed and Services Directory	Online	Tool for finding local native plant suppliers. Developed by the Xerces Society for Invertebrate Conservation.
Pollinator plants	Plant Lists and Collections	Online	Searchable lists of beneficial native plants for pollinators by light requirements, soil moisture requirements and bloom period. Developed by the Lady Bird Johnson Wildflower Center (University of Texas at Austin) and the Xerces Society for Invertebrate Conservation.
Native bees	Pollen Specialist Bees of the Eastern United States	Online	Pollen specialist bees of the eastern United States, the states in which they are found, and their host plant(s). Developed by Jarrod Fowler and Sam Droege.
Native bees	Pollen Specialist Bees of the Central United States	Online	Pollen specialist bees of the central United States, the states in which they are found, and their host plant(s). Developed by Jarrod Fowler.
Native bees	Pollen Specialist Bees of the Western United States	Online	Pollen specialist bees of the western United States, the states in which they are found, and their host plant(s). Developed by Jarrod Fowler.
Pollinator plants, insects	Holm, H.N. 2014. Pollinators of native plants: attract, observe and identify pollinators and beneficial insects with native plants. Minnetonka, MN: Pollination Press. 320 p.	Book	Perennial native plants by U.S. region and the beneficial insects associated with them.
Pollinator plants, native bees	Wilson, J.O.; Messinger Carril, O. 2016. The bees in your backyard: a guide to North America's bees. Princeton, NJ: Princeton University Press. 288 p.	Book	Pollinator plantings by U.S. region as well as extensive coverage of the identification and life history of common native bees.

Topic	Resource	Type	Description/developer
Bee monitoring, specimen preparation	The Very Handy Manual 2.0: How to Catch and Identify Bees and Manage a Collection	Online	Several different bee sampling methods, including bee bowls and netting, and detailed instructions on how to prepare specimens, care for an insect collection and begin to identify species. Developed by Sam Droege.
Bee monitoring	Streamlined Bee Monitoring Protocol for Assessing Pollinator Habitat	Online	Streamlined protocol for a non-lethal visual survey method that involves surveyors walking along a transect to categorize species into broad groups. Minimal training required. Focuses on bee abundance. Developed by the Xerces Society for Invertebrate Conservation.
Bee monitoring	National Protocol Framework for the Inventory and Monitoring of Bees	Online	Detailed guidelines on using pan traps for both short- and long-term monitoring of bee communities. Widely adaptable to a range of monitoring projects. Developed for the U.S. Fish and Wildlife Service by Sam Droege and colleagues.
Bee monitoring	Pacific Northwest Bumblebee Atlas	Online	Guidelines that could serve as a template for creating photo-based monitoring efforts focused on bumblebees. Developed by the Xerces Society for Invertebrate Conservation.
Bee monitoring	Pennsylvania Bee Monitoring Program	Online	A program designed for statewide monitoring, but the techniques are highly adaptable. Excellent demonstration videos on bee bowl, blue vane trap, and netting techniques, with datasheet examples. Developed by the Lopez-Uribe lab at Pennsylvania State University.
Pollinator monitoring	Roadside Revegetation: An Integrated Approach to Establishing Native Plants and Pollinator Habitat	Online	Multiple protocols for monitoring bee abundance as well as bee and butterfly diversity using a non-lethal visual survey method that groups bees and butterflies into broad categories. Developed for roadside revegetation projects by the U.S. Department of Transportation, Federal Highway Administration and adaptable to various other projects.

Topic	Resource	Type	Description/developer
Bee monitoring	Campbell, J.W.; J. L. Hanula. 2007. Efficiency of Malaise traps and colored pan traps for collecting flower visiting insects form three forested ecosystems. Journal of Insect Conservation. 11: 399–408. http://doi.org/10.1007/s10841-006-9055-4.	Journal article	Comparison of two lethal passive bee trapping methods—pan traps and Malaise traps—in forested systems in the southeastern United States.
Bee monitoring	Cane. J.H.; Minckley, R.L.; Kervin, L.J. 2000. Sampling bees (Hymenoptera:Apiformes) for pollinator community studies: pitfalls of pan-trapping. Journal of the Kansas Entomological Society. 73:225–231.	Journal article	Description of bias in pan trapping methods and useful considerations for using these lethal methods.
Bee monitoring	Grundel, R.; Frohnapple, K.J.; Jean, R.P.; Pavlovic, N.B. 2011. Effectiveness of bowl trapping and netting for inventory of a bee community. Environmental Entomology. 40(2): 374–380. https://doi.org/10.1603/EN09278.	Journal article	Description of a common and intensive method for monitoring bee communities—a combination of passive pan traps and netting—as complementary techniques to gain a detailed inventory of a bee community.
Bee monitoring	Mathis, C.L.; McNeil, D.J.; Kammerer, M.; Larkin, J.L.; Skvarla, M.J. 2024. Distance models reveal biases associated with passive trapping methods for measuring wild bee abundance. Frontiers in Ecology and Evolution. 12: 1380622. https://doi.org/10.3389/fevo.2024.1380622.	Journal article	A visual survey methodology for obtaining more accurate measures of bee abundance at sample sites by accounting for detection probability.

APPENDIX 3

Bee Washing, Drying, and Pinning Protocols

The following guidelines are adapted from The Very Handy Manual 2.0: How to Catch and Identify Bees and Manage a Collection (2024) by Sam Droege.[1]

Strainer Washing

Pinning bees directly from water or alcohol usually results in matted hairs and altered colors, along with a good coating of pollen, scales, and other detritus picked up from the sample. Washing and processing bees using the following process results in well-groomed specimens that can exceed the quality found when hand collected.

Note: If you have a sample with a lot of bumblebees, wash and dry them in small batches of five or so bees at a time.

1. Strain the bee specimens out of the alcohol (make sure to dispose of alcohol in the correct disposal container, not down the sink).

2. Remove wet label from inside vial and set it aside in a petri dish. It is very important to keep track of this label.

3. Return bee specimens to a vial, sample cup, or jar. Add a small amount of warm water and Dawn (original scent) dish washing liquid (pea sized amount or less), cap the container, and very vigorously swirl/ shake the specimens for about 60 seconds.

4. Place specimens back into the strainer and rinse under tap water until no more suds are present. Use your hand to break the force of the water to protect the specimens.

5. Gently shake off loose water and use a towel to blot out as much excess water on the bottom of the strainer as possible.

6. Only if working with a large sample of very hairy bees: Dip the strainer into a bowl of fresh alcohol.

7. Dump the specimens onto a stack of 3 to 6 paper towels and fold the paper towels over the specimens and pat them dry. This step is often forgotten, but it is important.

[1] Droege, S. 2024. **The very handy manual 2.0: how to catch and identify bees and manage a collection.** Laurel, MD: U.S. Geological Survey, Eastern Ecological Science Center. 74 p. https://bio2.elmira.edu/fieldbio/beemovies/beemanual/beemanual.pdf (accessed 6 June 2025).

Hair Drying

1. Dump (or transfer with forceps) the specimens from the paper towel into a canning jar with a mesh lid.

2. You may want to dry bees in several batches based on size; small bees will take less time to dry than large hairy bees such as bumblebees.

3. Turn on hair dryer. Use high heat, although heat is not always necessary, particularly if the specimens are rinsed in quick evaporating alcohol.

4. Hold the jar on its side at an angle and place hair dryer pointing into the jar as close as possible.

5. While drying, shake the specimens back and forth vigorously. When wet, specimens are very flexible and tough, so they can take a moderate amount of bumping around.

6. As the specimens dry, they will come loose from the bottom and whirl around in the dryer's wind; continue shaking the specimens.

7. Small short-haired specimens are dry once their wings are flexed away from their body and their hairs are not matted. Bumblebees and long-haired specimens take longer. Depending on your hair dryer, your technique, and the specific specimens you are working with, drying may take anywhere from 1 to 3 minutes.

8. Dump bees from jar into petri dish with the label from the sample that you set aside earlier. Note: If you have bumblebees in your sample, build them a paper towel "nest" to hold them upright in the petri dish.

9. If you are washing a number of samples at a time before you start pinning, put the lid on the petri dish and a small piece of wet paper towel inside to prevent bees from drying out too much before you pin them.

Pinning

1. Carefully take the petri dish of dry bees to a dissecting scope.

2. Using forceps, place one bee at a time on a small piece of foam with the head facing away from you.

3. Note: If the bee is a male or requires a special pinning technique, flip the bee onto its back and open the mandibles or pull the genitals.

4. With the bee resting on its belly, rest a finger lightly on the bee's abdomen to hold it in place.

5. Most bees should be pinned with a size 1 insect pin. Large bumblebees require a size 2 pin. If a bee is so small that a pin will obscure the whole thorax, glue it to a point on the right side of the body.

6. Insert the pin on the right side of the bee next to the tegula (Fig. 23). Note: The only exception to this is with Ceratina spp., which should be pinned through the metanotum (Fig. 23).

7. Pin slowly and make sure the pin is straight, adjusting the angle as needed.

8. Push the bee up to 9 mm below the top of the pin.

9. Place the bee on a large piece of foam to the right of the wet label that was in the bee's original vial.

10. Transfer all pinned bees to a bee box and record all samples on the outside of the box.

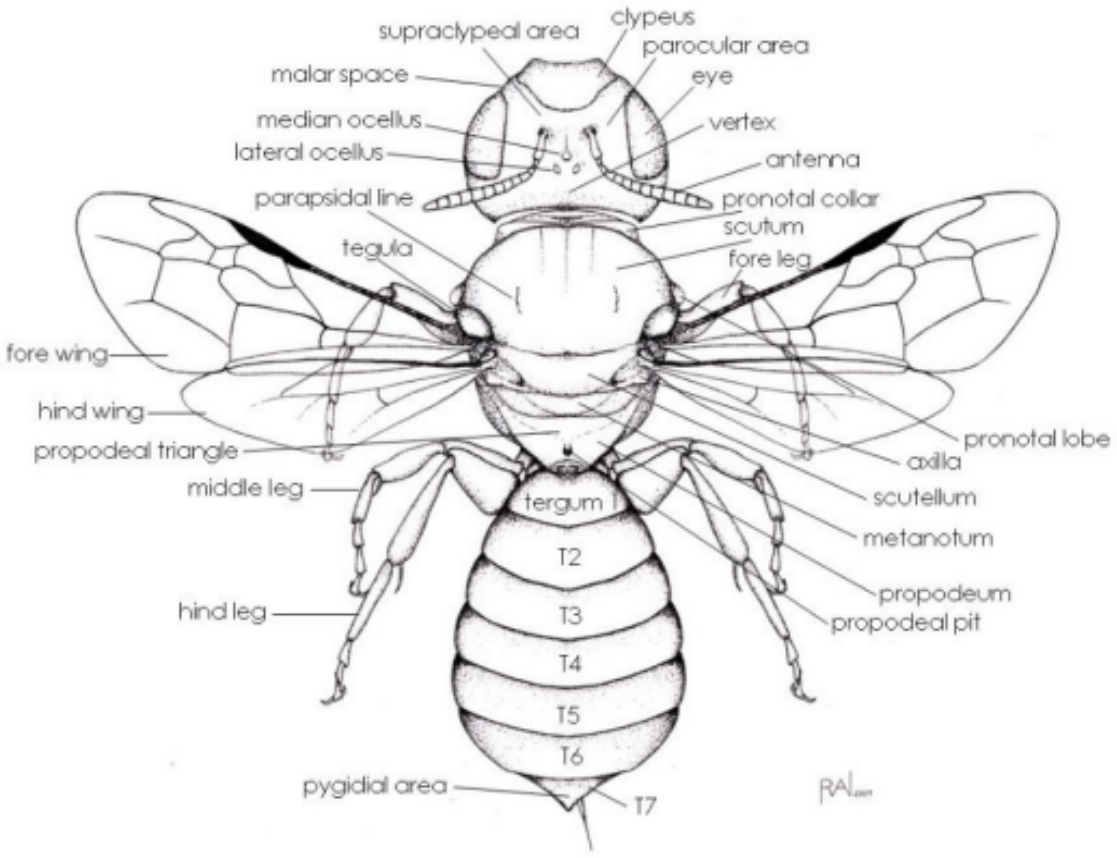


Figure 23.—Diagram of a bee. Source: Droege, S. (2024), Rebekah Nelson, illustrator.

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