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PERSPECTIVE

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Beyond the basics: a perspective on barriers and opportunities for scaling up biochar production from forest slash

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Abstract

Biochar production from woody biomass generated during forest management (slash) offers significant benefits for soil health and carbon emissions, yet its adoption remains limited in the western United States (U.S.). To address this challenge, the U.S. Department of Agriculture (U.S.D.A.) Forest Service Rocky Mountain Research Station organized two workshops focused on forest management-centric biochar production. These workshops convened a diverse group of stakeholders, including investors, land management practitioners, industry professionals, and research scientists, each with unique roles in slash-based biochar production. This article presents a synthesis of the insights and perspectives gathered from these workshops, aiming to identify barriers and propose viable pathways for overcoming them. The barriers encompass governance issues such as policy and permitting, economic challenges related to costs, funding, and market stability, technological hurdles concerning methods and equipment, and a need for further research and improved science dissemination. In response to these challenges, workshop attendees collaboratively outlined specific strategies to reduce these barriers. These strategies emphasize the expansion of operational initiatives, the development of proactive policies, the stabilization of biochar markets, and the generation of additional case studies showcasing the effects of biochar amendments across various soils and environments. Collectively, the insights gleaned from this workshop series provide a comprehensive roadmap outlining both the struggles and the necessary actions and investments required to enhance the scale of slash-based biochar production and application in the western U.S.

Highlights

- Intertwined policy, economic, technology, and knowledge barriers underpin pervasive biochar adoption issues.
- Managers face pervasive challenges with permitting, slash handling costs and uncertain biochar application benefits.
- Pathways forward involve setting goals, streamlining permits, enhancing science communication, and further case studies.

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Graphical Abstract

1 Introduction

Despite compelling evidence pointing to the potential improvements in soil health and carbon sequestration offered by biochar (Woolf et al. 2010; Pachauri et al. 2014; Lehmann et al. 2021), its scale of production and use remains strikingly limited in the western U.S. This issue becomes more pressing when considering the abundant stockpiles of forest biomass waste (slash) in the western U.S., generated primarily through widespread land management activities like timber harvesting and forest fuel reduction practices. Remarkably, this vast source of biomass, estimated at over 350 million dry tons annually (Buford and Neary 2010), is poised to grow further with initiatives such as the National Cohesive Wildland Fire Management Strategy (Executive Order (E.O.) 14008), which initiates a plan to thin overstocked forests across an additional 50 million acres in the next decade (U.S.D.A. Forest Service 2022). Presently, waste biomass usually meets with one of two outcomes: it is either burned, releasing carbon into the atmosphere and heightening wildfire risks, or left to decompose, which also emits carbon and adds to forest fuel loads (Han et al. 2018). Both scenarios represent missed opportunities for carbon sequestration. Indeed,

the recognition of the climate and soil benefits that can be achieved by utilizing this waste biomass for biochar production are well-documented (Page-Dumroese et al. 2016). Biochar production offers a sustainable alternative for waste biomass disposal when it cannot be burned due to fire danger, air quality concerns, or other operational constraints. Fully realizing biochar production and use from forest slash is a complex challenge, primarily due to the intricate array of barriers that land managers may encounter when implementing biochar-based practices.

Incorporating biochar into land management strategies offers a multifaceted solution to several pressing environmental challenges. Biochar's unique physicochemical properties, such as its high ion exchange capacity and porous structure, make it an ideal candidate for improving soil health, particularly in landscapes plagued by acidic soils and contaminants (Bolan et al. 2022; Li et al. 2018; Rodriguez-Franco and Page-Dumroese 2021). Moreover, its slow decomposition rate offers a long-term solution for carbon sequestration, aligning with broader climate goals (Wang et al. 2016). Despite these advantages, limited investment in biochar production and application persist in the western U.S., where slash utilization is rarely considered for commercial or environmental purposes (Galinato et al. 2011). While current practices predominantly involve pile burning of this biomass, which has negative implications for air quality, soil health, and carbon emissions (Zhang et al. 2013; Korb et al. 2004; Finkral et al. 2012), repurposing forest slash for biochar production provides a unique, dual opportunity to serve broader efforts to mitigate wildfire risks and provide a sustainable, plentiful and low-cost source of biomass for biochar production (Page-Dumroese et al. 2017). However, transitioning from the current state of forest management to one that fully integrates biochar production requires initially identifying barriers that managers encounter. These barriers encompass economic, logistical, and scientific constraints that are underpinned with policy and cultural frameworks that may limit new methods. Nevertheless, delving deeper into the specifics of these obstacles has proven to be challenging, given the diverse landscapes, management priorities, and available resources in the western U.S. Identifying and addressing these barriers demands a broad perspective and a multidisciplinary approach to effectively determining the fundamental impediments hindering the implementation of biochar-based practices in climate-smart forest operations across the western U.S.

Here we presented a synopsis of the barriers to biochar production and application in the western U.S. While substantial research has focused on the technical aspects of biochar production, chemical properties, application rates and methods, and its use as a wildland soil amendment, our intention here is to further expand the focus to encompass the logistical, economic, policy, information, and operational challenges that land managers encounter when attempting to adopt and scale biochar-based practices. Through an exploration of these barriers, based on firsthand experiences, our goal is to identify the broader array of issues surrounding the slow adoption of biochar-based practices in the western U.S.

In particular, this article leverages the perspective gained from recent workshops hosted by the U.S.D.A. Forest Service, Rocky Mountain Research Station, which were collectively titled "Beyond Biochar Basics: Scaling Up and Moving the Needle." These workshops convened over 100 experts from diverse backgrounds, spanning industry, land management, private investment, and research sectors, all sharing a deep interest and expertise in biochar. Our intent with these events is to capture and disseminate their collective knowledge and experiences concerning biochar. In this article, we provide a comprehensive overview of the challenges that land managers frequently confront in relation to biochar production or application in forest ecosystems. Our specific objectives are: (1) identify and categorize the various obstacles hindering the adoption of biochar practices in forest management and (2) offer practical, science-based pathways for mitigating these obstacles. Through the collection of these firsthand perspectives, we seek to educate and broaden the discourse surrounding the challenges that persist in the adoption of biochar across the extensive forested regions of the western U.S.

2 Barriers to biochar-based practices

2.1 Overview

The workshops illuminated the multifaceted challenges that impede the adoption of biochar production and application in forest management across the western U.S. These challenges are broadly categorized into three main areas: policy, process, and application (Fig. 1).

- Policy-related barriers, such as regulatory hurdles and permitting complexities, often act as external constraints that are beyond the immediate control of local land managers. These issues can stymie biochar projects at any stage, from inception to implementation.
- Process-related and inherent cultural barriers, encompass logistical challenges like feedstock quality, site selection, new field technology and production methods. Notably, these barriers vary significantly depending on whether biochar production occurs

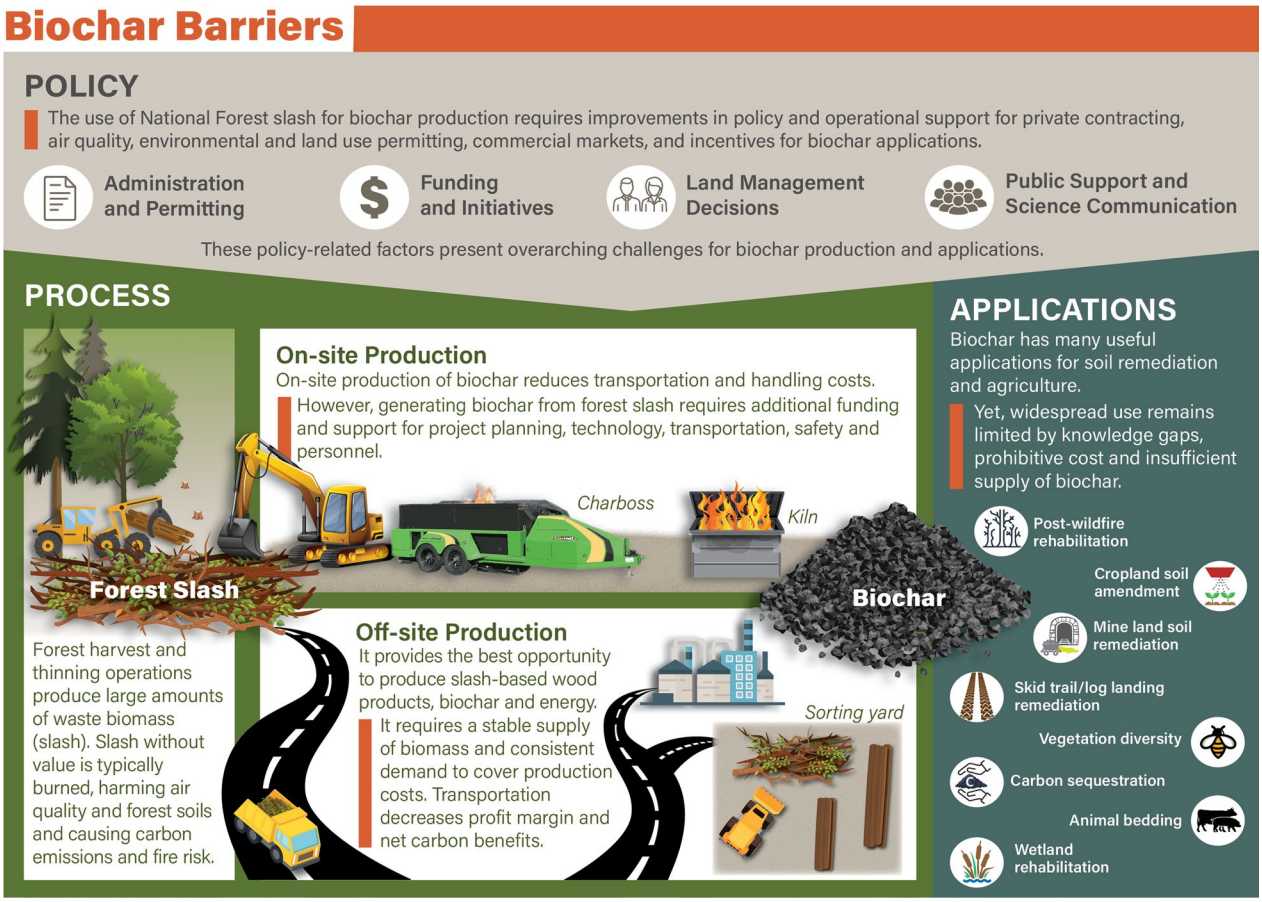

Fig. 1 Overview of common barriers (policy, process and applications) to slash-based biochar production

in situ or requires transporting biomass to an off-site facility.

- Biochar application-related barriers primarily revolve around knowledge gaps concerning the effective use of biochar for soil and vegetation enhancement.

Further, interrelated challenges often compound the implementation of biochar projects, to the extent that a single barrier can derail an entire initiative. These obstacles not only hamper project execution, but also raises concerns about the return-on-investment when compared to simpler, traditional practices like open burning. A few recurring themes across the nearly 100 noted challenges covered by the workshop attendees include the urgent need for improved science communication, particularly for production process and application (Fig. 2). This suggests that while many policy-related issues may be well-understood, significant gaps remain in the practical and applied dimensions of biochar use. Additionally, economic considerations, such as the cost of production and market stability complicate increased production and use, highlighting the issues of supply and demand for biochar. The subsequent sections provide insights into the broad array of obstacles discussed by the workshop attendees, offering experience-based insights and implementable strategies for land managers with the goal of scaling up biochar operations.

2.2 Policy and regulatory barriers

During discussions with workshop participants, several policy and regulatory barriers emerged as significant obstacles to the adoption of biochar production and application in forest management. Among these, the stringent requirements for air quality permits were a particularly burdensome hurdle. These permits vary from state-to-state and can be expensive, especially for small logging operators and for equipment that produces fewer emissions than traditional open burning methods, which paradoxically requires minimal permitting. This discrepancy creates a financial disincentive for adopting cleaner biochar production methods. Additionally, the absence of policy language specifically addressing the disposal of

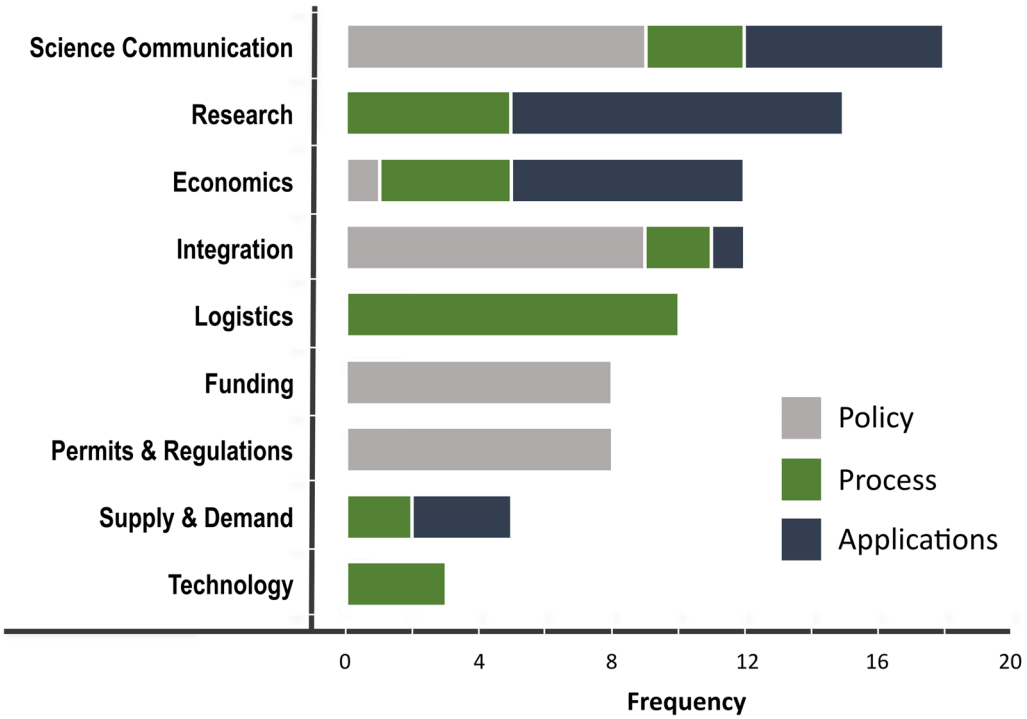

Fig. 2 Frequency of specific types of barriers to woody slash-based biochar production discussed during the workshop series

unmerchantable wood and residues further complicates the landscape. This gap in policy makes it difficult to utilize slash piles for bioenergy or biochar, despite their potential benefits. Moreover, the lack of long-term contracts for wood supply from national forests hampers commercial investment in bio-products.

Another layer of complexity arises from the regulatory requirements for biochar intended for sale as a soil amendment, particularly for agricultural users. While guidance exists, such as that provided by the U.S. Biochar Initiative (https://biochar-us.org/labeling-guidelines-biochar-products), the question of how biochar amendments should be registered with relevant state or federal agencies remains. This is particularly pertinent given that biochar technology and practices are rapidly evolving. For instance, in Canada, biochar enjoys a more lenient regulatory status (CRC, c. 666 2023), which facilitates its application in soil. Furthermore, we observed that there is a general lack of awareness among stakeholders about existing incentives, such as the U.S.D.A. Natural Resources Conservation Service's Conservation Enhancement Activity (Biochar production from woody residue; E384A), that promotes on-site production and forest use of biochar to help reduce wildfire risk and promote soil health. This underscores the need for improved communication to ensure that private landowners are fully informed of the policies, benefits, and incentives available for biochar production and application.

Overall, the benefits from producing and using biochar as an alternative to open burning of waste biomass comes with a need to develop adaptive and coherent policies within and across land management agencies. Specifically, to support a cost-effective biochar and bioenergy process that uses unmerchantable wood for viable products, a holistic policy and regulatory approach is critically needed that addresses air quality, wildfire risk reduction, forest product provisions, ecosystem benefits, and management-related concerns. However, developing such cohesive policy instruments will require a sustained and concerted effort.

2.3 Integration and support

Transitioning from traditional methods of forest slash disposal to biochar production presents several operational challenges. One key consideration is the need for novel and specialized equipment, along with associated training of personnel. Further, beyond monetary costs, this shift also necessitates the development of more comprehensive procedures for handling and preparing slash, whether for on-site biochar production or transport to off-site facilities. Day-to-day factors such as storage, ongoing maintenance costs, and the need for sharing

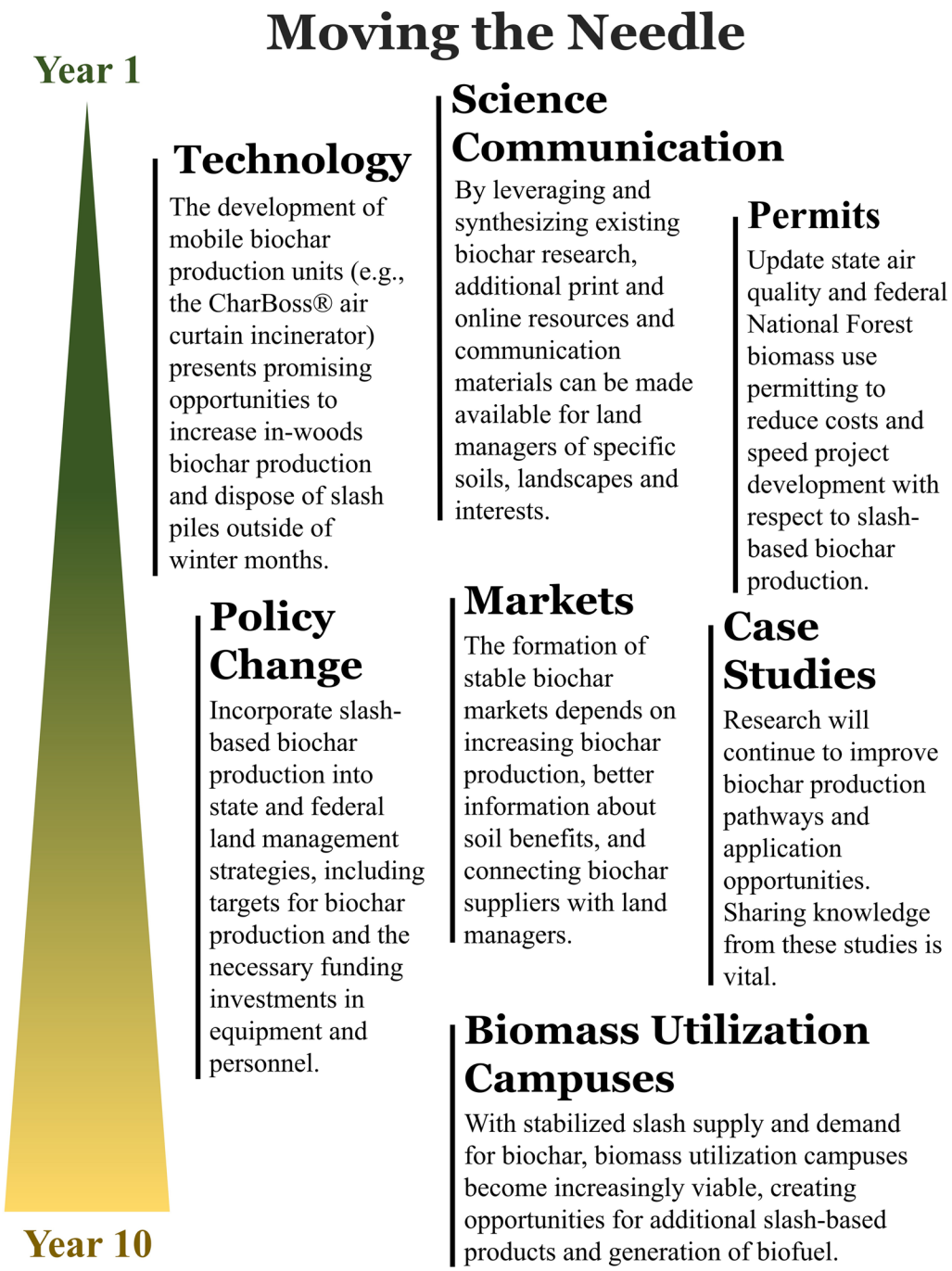

Fig. 3 Pathways for overcoming barriers to woody slash-based biochar production

equipment between multiple independent organizations further complicate the integration of biochar production into existing forest management practices. These logistical constraints are amplified when operations are subject to differing regulations for federal, state, or tribal entities. Compared to the more straightforward, albeit environmentally detrimental, practice of open burning, these additional logistical steps can be daunting, especially when operational resources and timelines are narrow for accomplishing the desired outcomes. However, an initial evaluation of the scale of opportunity for slash-based biochar production can guide the integration of new methods and equipment into existing operations. For example, in some areas investments in biochar production could

entirely replace current methods of slash reduction, while in others, it may be more feasible to implement biochar practices only in specific areas (e.g., campgrounds), or as staffing and operational constraints permit.

Agency, public, and private support for biochar projects can be a significant barrier to the adoption of biochar production methods on public lands. Despite the critical role of public opinion in shaping land management activities, land managers often face challenges in conveying complex information about the environmental and safety benefits of biochar compared to traditional practices. Recent research suggests that virtual platforms could offer a method for interacting with the public, but its potential remains underutilized (Floress and Cohen 2022). Another barrier arises from the lack of future-oriented decision-making approaches, such as strategic foresight, in current land management practices. Such approaches are needed to better inform both public and internal stakeholders about potential future scenarios, including the benefits of biochar production in mitigating risks associated with accumulating forest slash. However, the adoption of these forward-thinking strategies is often hindered by uncertainties related to climate change, staffing levels, educational needs, and budgetary considerations, making it challenging to build long-term resilience into forest management plans.

2.4 Economics

Financial constraints emerged as a significant barrier to the adoption of slash-based biochar production during workshop discussions, affecting both land managers and commercial enterprises. While forest management activities generate abundant slash, the availability of this material can be constrained by factors such as location, harvest season, and method of collection. Therefore, one of the key economic challenges lies in securing a consistent and competitively priced supply of biomass. For example, in temperate forests, forest slash production and transport may be feasible only during specific months when conditions are optimal and fuel treatment activities are permitted. Additionally, the quality and quantity of forest slash can fluctuate, impacting the efficiency, quality, and economics of biochar, especially when a consistent product is needed for specific markets.

If waste biomass is planned to be moved to a fixed bioenergy or biochar plant, then another economic hurdle is the cost associated with slash handling and transportation. Forest slash is often located in remote areas, making the logistics of collection and transportation financially challenging. These costs can escalate with the need for specialized equipment and personnel. While existing personnel, such as wildland firefighters, could potentially be deployed for in-woods slash processing in the off-season, the timing of biochar production would need to align with their availability. In-woods biochar production, utilizing mobile kilns or specialized pyrolysis equipment, presents another opportunity for more efficient biochar production by reducing the need for biomass transportation to centralized facilities. In general, transporting biochar as a more valuable, finished product is more efficient than transporting biomass as a raw material. However, the decision between these two options hinges on various factors that can influence costs, including biomass supply, production scale, and biochar demand.

Despite the multifaceted utility of biochar, which includes applications ranging from soil amendment or use in livestock feedlots to carbon sequestration and renewable energy, commercial markets for biochar remain underdeveloped in many regions of the western U.S. Workshop participants specifically identified the uncertain cost and supply of biochar as significant barriers to its broader adoption, particularly among larger investment groups seeking to build market connections with commercial agriculture. Similarly, the often-fluctuating demand for biochar further complicates the scalability of production efforts and investments. These market-related challenges, centering around inconsistent supply and demand, create a perpetual cycle of uncertainty that adversely affects both producers and consumers. To address these barriers, there is a pressing need for increased awareness, targeted research, and supportive policies aimed at stabilizing and expanding biochar markets and building long-term connections between forestry and agricultural sectors.

2.5 Research a technology

A wealth of information about biochar is readily available, exemplified by resources such as the "Biomass to Biochar: Maximizing the Carbon Value Pacific Northwest U.S. Assessment" (Amonette et al. 2021a, b). Nevertheless, during the workshops, attendees emphasized a pressing need for additional case studies that demonstrate the diverse effects of biochar applications across various methods, biochar types, soils, and environmental conditions. These case studies not only serve to validate expected outcomes, but also provide valuable examples of how to develop and implement biochar-based practices in real-world scenarios. Given the substantial variability between sites, including differences in edaphic properties, climate, and biochar properties, the expected benefits of biochar production and application can differ significantly. Therefore, a more extensive portfolio of diverse case studies will enhance land managers' ability to validate expected outcomes and broaden their awareness and understanding of biochar's potential benefits.

Concerning technological barriers, there is an urgent need for improved methodologies and tools capable of accurately quantifying and assessing wood biomass volume and characteristics in forest slash piles. This information is invaluable at both the individual pile scale and for larger spatial assessments, which help determine the most appropriate locations for deploying technologies at various scales. Precise quantification of slash quality and stocks refines forest management plans for slash handling and disposal while identifying commercial prospects for slash utilization. However, developing and implementing new methodologies and technologies for slash inventory and prediction presents challenges. Field-based methods that involve accessing and sampling slash piles in diverse and often isolated locations pose logistical challenges across extensive forested regions. Aerial imagery-based alternatives also have limitations, especially when collecting information underneath forest canopies. These challenges are compounded by the inherent variability in slash pile composition, influenced by factors such as tree species and the age of the slash material, making quantification and characterization even more complex.

In-woods biochar production presents opportunities for significant cost savings by replacing the transportation of bulkier forest slash with the reduced volume of biochar produced. However, its success is critically dependent on technological advancements in specialized pyrolysis systems, including mobile kilns and air curtain burners that reduce emissions. Mobile units are one method to balance efficient biochar production while reducing adverse effects on soil, air quality, and wildfire risk. The current market offers a diverse array of mobile systems, each characterized by distinctive features and capital requirements. However, challenges abound in this arena. For example, relatively straightforward solutions like metal-walled kilns offer low-capital entry points for biochar production. More technologically advanced units (e.g., air curtain burners) are more mobile and reduce emissions but require a higher capital investment. Furthermore, the rapid evolution of mobile kiln technology necessitates immediate research efforts to comprehend the nuances in biochar production efficiency, emissions control, economic viability, training requisites, and scalability across various kiln designs and biomass feedstocks. As noted, this can be compounded by waste biomass variability, which magnifies the complexity of integrating in-woods biochar production into forest management practices. In-woods processing urgently requires additional knowledge and data around economic feasibility, environmental stewardship, and safety considerations.

2.6 Science communication

Throughout the workshops, participants were given the task of identifying topics that could benefit from further research or enhanced communication to facilitate the expansion of biochar production and utilization. Interestingly, some of the most frequently mentioned subjects, such as determining suitable biochar application rates, are already well-documented in existing knowledge repositories. This observation brings to the forefront a substantial communication gap between the generation of knowledge and its practical application in the field of biochar-based land management practices.

The discussions predominantly revolved around critical needs for the development of materials focused on in-woods biochar production methods and rates, understanding the relationship between biochar and carbon sequestration, post-wildfire and mine land biochar applications, and optimizing slash pile construction for biochar production. Additionally, participants emphasized the importance of local field trials and access to demonstrations to bolster the confidence of land managers in creating and using biochar.

Workshop attendees showed a clear preference for communication materials that employ infographics and concise summaries to convey critical knowledge and methods. These formats effectively convey information swiftly and succinctly, unlike more in-depth research articles. Ultimately, bridging the gap between scientific research and the practical implementation of biochar-based practices in the field, stands out as one of the most pressing, yet potentially solvable obstacles to hastening the adoption of biochar-based land practices in the western U.S.

3 Pathways forward

The following sections draw upon insights derived from the discussions with workshop attendees regarding near-term (< 10 years) opportunities to reduce barriers in biochar policy, processes, and applications (Fig. 3). Their experience and expertise, coupled with the collective knowledge of the author group, inform this section and build from the identified barriers that hinder adoption of biochar-based practices in forest land management in the western U.S.

3.1 Establishing goals

In light of recent funding measures, there is a unique opportunity to bolster the realization of biochar targets across public lands. Current funding streams, exemplified by the Bipartisan Infrastructure Law (Public Law

117-58) and the Inflation Reduction Act (Public Law 117-169), present a viable mechanism to enhance land management activities. These include initiatives aimed at reducing wildfire risks, which, in turn, amplify the demand for forest slash reduction efforts. Harnessing these funds proactively could serve as a catalyst for the adoption of production equipment and biochar application in forest land practice, aligning seamlessly with funding objectives to curtail emissions, sequester carbon, and advance soil fertility through renewable and sustainable land practices.

Many public land management agencies set annual goals and expectations for their programs. Yet currently, there are no consistent requirements or incentives for state and federal land management agencies to engage in biochar production or use. Currently, the Bipartisan Infrastructure Law (Public Law 117-58) is helping the U.S.D.A Forest Service fund contractors and field crews to remove vegetation, and to the extent practicable produce biochar or other products with assistance from locally based organizations (e.g., youth conservation corps, Tribal youth). Although the law doesn't set specific biochar targets, it does encourage its production. Given the diverse landscapes, budgets and pressing management issues across the many forested regions of the western U.S., it's challenging to mandate specific biochar goals for land managers. However, the law offers a broad alternative pathway to promote biochar adoption in forest land practices. By specifically emphasizing the importance of removing flammable vegetation and creatively utilizing the resulting waste biomass, the Law thereby provides an implicit framework for biochar integration. In this context, setting achievable inter-agency goals for land management and biochar production could pave the way for scaling up biochar-based practices and serve as a foundation for future production increases.

To increase biochar-related practices, we need improved accounting of biochar production and use across public lands. Monitoring the quantity of biochar produced and applied on public lands not only provides valuable data for assessing the scale of biochar production, but also allows for comparisons between different practices and identification of critical barriers where biochar use remains limited. Such information can pinpoint areas best suited for biochar production and use, as well as areas where biochar-based practices may be impractical or in need of additional support. Moreover, enhancing metrics for tracking biochar production and applications provides a more robust foundation for evaluating the current and future environmental benefits of biochar, including emission reduction, carbon sequestration, soil fertility improvement, and contaminant remediation. In summary, improving oversight and the monitoring of biochar production and use will inform decision-making when setting targets for biochar utilization in land practices across public lands.

3.2 Permits

The process of securing air quality permits for biochar production from forest slash currently reduces the application of climate-smart initiatives advocated at the federal and state levels. Pile burning, despite emitting more harmful substances than most biochar production methods, often faces less stringent air quality permit requirements in various States and counties. To facilitate the expansion of production, there is a need to develop classifications or exemptions that streamline the approval process for air quality permits, particularly for well-established technologies such as air curtain burners. Achieving this goal is most likely through collaborative efforts that leverage shared resources and information across jurisdictions. A united effort provides a coherent educational message to policymakers and broadly applicable pathways for refining the permitting process. In addition to realigning permitting procedures with desired environmental outcomes, it is essential to devise policies that incentivize biomass utilization while considering the adverse environmental impacts of pile burning. This approach should also account for the non-market values associated with alternatives to pile burning, such as climate and ecosystem benefits, thus promoting a more holistic and sustainable approach to forest waste management.

3.3 Science communication

Science communication materials are one method that promotes waste biomass-based biochar production and utilization. They inform and generate interest, but also catalyze operational and policy transformations. The need for well-disseminated information that elucidates specific benefits of biochar is paramount. Such dissemination bolsters awareness and serves to support innovation and initiative. Moreover, science communication is an indispensable tool to enlighten legislators and decision-makers at all levels about the advantages associated with the conversion of forest slash into biochar. To achieve maximum impact, it is imperative that scientific information is succinct, captivating, and easily digestible. This ensures that all stakeholders and decision-makers can learn the merits of adopting this technology. Importantly, providing evidence-based illustrations of successful projects and technologies from diverse geographical areas are essential for promoting biochar practices in new locations.

Science communication materials can also facilitate community engagement, fostering transparency and

trust among stakeholders. Beyond raising awareness, they can serve as advocacy tools for policy and process changes that promote biochar production and utilization. Effective science communication fosters and supports collaboration among researchers, practitioners, and policymakers and ensures that stakeholders remain informed of the latest developments in biochar research and applications, thus spurring continuous improvement and innovation. In the context of slash-based biochar production, effective science communication is not just informative, but also a critical catalyst for transformative change in how our communities view and utilize biochar.

3.4 Case studies

Enhancing science communication provides a step forward in breaking down barriers to the adoption of biochar production and use, but biochar-related uncertainties still require further investigation. These uncertainties encompass biochar production, feedstock and soil types, vegetation responses, application rates, and use for inorganic and organic contaminant remediation. Given the diversity of forest systems, soils, climates, and vegetation in the western U.S., it's imperative to address these uncertainties comprehensively. This can be achieved through documentation of case studies and installation of additional study areas as the opportunities arise. Case studies are an invaluable tool for developing a wider understanding of production and application methods tailored to the specific needs and environments. Notably, recent proposals have emerged to establish a diverse research network dedicated to this purpose (Amonette et al. 2021a, b). Additionally, alongside the need for empirical research and funding, there is an immediate demand for improved management, synthesis, and simplified accessibility of both new and existing biochar-related study data and conclusions. By creating larger, more accessible biochar data collections and research questions can be addressed on a broader scale, while also providing land managers with a source for research products and data that are relevant to the ecosystems they operate in, as well as to their project conditions and goals.

3.5 Supply and demand

The proliferation of innovative biochar production technologies promises to significantly expand accessibility and capacity for in-woods production of biochar. A variety of kiln designs, available at different price points and production capacities, now enable biochar production at practically any scale. Moreover, newer kilns are designed to reduce emissions and fire risks (Jang et al. 2017; Lee and Han 2017), providing unique opportunities to dispose of slash in sensitive areas. Systems have also been developed to efficiently distribute biochar on forested sites, further expanding opportunities for forest managers to use biochar to achieve land management goals related to site restoration, soil health, and carbon sequestration. (Page-Dumroese et al. 2016).

The adoption of in-woods biochar production carries a notable advantage, namely, reducing the dependence on off-site biochar markets. Instead, it shifts the primary focus towards improving on-site ecosystem services. Ecosystem service benefits include enhanced water storage and carbon sequestration. On non-federal lands there is also the potential to generate revenue through carbon offset credits which could also finance biochar projects. In this paradigm, the cost associated with biochar production and utilization aligns with the willingness to invest in heightened ecosystem services. These benefits extend beyond carbon sequestration and encompass a range of advantages, including the reduction of smoke emissions from pile burning. This shift in perspective underscores the pivotal role of in-woods biochar production in fostering sustainable land management practices and realizing environmental objectives.

For commercial operations that transport waste woody biomass or biochar off-site, downstream markets and stable demand become critical. Broadly encouraging and subsidizing biochar utilization in public and private sectors can serve as a catalyst for these markets, particularly in the context of large-scale commercial biochar production, whether mobile or centralized. Recent subsidies for capital investment in biochar facilities and equipment (Campbell et al. 2018) have already had a notable impact on biochar supply, particularly in regions like the Pacific Northwest and California. However, there are additional opportunities to meet the growing demand for biochar production. On the supply side, there's an urgent need to improve terms associated with biomass procurement from federal lands, particularly for waste biomass, thus reducing investment risk for private partners who require a consistent, reliable supply of slash to ensure the viability of their operations. Currently, biomass left on site and burned for disposal may be considered a waste liability with net costs, whereas the same waste material, when removed and utilized, is regarded as a federal asset subject to a minimum revenue requirement. This requirement disincentivizes utilization. In addition, showcasing the tangible benefits of biochar for soil and vegetation on public lands can bolster demand across diverse land ownerships and uses. In certain regions, biochar production may scale up to a capacity capable of satisfying substantial and continuous biochar demands, especially in industries like agriculture. Such scaling offers the potential

to reduce production costs through economies of scale and a stabilized market as biochar usage becomes more widespread.

Expansive and stable biochar markets are poised to create a ripple effect of opportunities for more comprehensive utilization of forest slash-based products. In a future scenario where slash supply and value attain greater consistency, private enterprises can make more informed assessments of the profitability associated with substantial investments in centralized bioproduct facilities. These facilities, sometimes referred to as wood utilization campuses or biohubs, are economically preferential due to the ability to optimize the separation of roundwood and slash to extract maximum value. This includes capturing valuable resources such as sawlogs, post and pole materials, fuelwood, clean chips, dirty chips, and hog fuel, which can serve as the raw material for a diverse range of innovative products, including biochar. Centralized facilities also open more ideal avenues for the generation of bioenergy, encompassing heat, electricity, and biofuels, in addition to the production of items derived from common sawmill byproducts like sawdust, chips, and shavings. These byproducts can be transformed into particle board, pellets, or animal bedding. Such a comprehensive system represents pathways for maximizing the abundant environmental and societal benefits that can be harnessed from our forest biomass resources.

4 Conclusion

In response to the urgent need for sustainable forest management in the western U.S., we have identified critical barriers—encompassing policy, process, and application challenges—that impede the broader adoption of biochar in forest land practices. Notably, stringent air quality permits, logistical complexities, market uncertainties and knowledge gaps in effective biochar use present formidable obstacles. However, amidst these challenges, we learned promising strategies to overcome them. The biochar path forward can benefit from defining policies that encourage land management agencies, streamlining permitting processes to reduce costs and acknowledge benefits, improving science communication and outreach efforts, highlighting current and new case studies, and supporting the development of biochar markets. By embracing these strategies, we reduce the environmental impacts of open woody slash pile burning and harness the multiple benefits of biochar, from carbon sequestration to improved soil fertility. In doing so, we take a significant step towards sustainable land management practices that contribute to a healthier environment and a more resilient future.

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Author contributions
All authors contributed to the workshops, study conception and design. Material preparation, data collection and analysis were performed by DP, NC, DP-D and MH. The first draft of the manuscript was written by DP and all authors contributed to revisions across subsequent versions of the manuscript. Figures were developed by DP, TN and KH. All authors read and approved the final manuscript.

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Availability of data and materials
The data and presentations analyzed during the current study are available on the U.S.D.A. Forest Service Research Data Archive.

Declarations

Competing interests
The authors have no relevant financial or non-financial interests to disclose.

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References

Amonette JE, Archuleta JG, Fuchs MR, Hills KM, Yorgey GG, Flora G, Hunt J, Han H-S, Jobson BT, Miles TR, Page-Dumroese DS, Thompson S, Trippe KM, Wilson K, Baltar R, Carloni K, Christoforou C, Collins DP, Dooley J, Drinkard D, Garcia-Pérez M, Glass G, Hoffman-Krull K, Kauffman M, Laird DA, Lei W, Miedema J, O'Donnell J, Kiser A, Pecha B, Rodriguez-Franco C, Scheve GE, Sprenger C, Springsteen B, Wheeler E (2021) Biomass to biochar: maximizing the carbon value. Report by Center for Sustaining agriculture and natural resources, Washington State University, Pullman WA. csanr.wsu.edu/biomass2biochar.

Amonette JE, Blanco-Canqui H, Hassebrook C, Laird DA, Lal R, Lehmann J, Page-Dumroese D (2021b) Integrated biochar research: a roadmap. J Soil Water Conserv 76:24A-29A. https://doi.org/10.2489/jswc.2021.1115A

Bolan N, Hoang SA, Beiyuan J, Gupta S, Hou D, Karakoti A, Joseph S, Jung S, Kim K-H, Kirkham MB, Kua HW, Kumar M, Kwon EE, Ok YS, Perera V, Rinklebe J, Shaheen SM, Sarkar B, Sarmah AK, Singh BP, Singh G, Tsang DCW, Vikrant K, Vithanage M, Vinu A, Wang H, Wijesekara H, Yan Y, Younis SA, Van Zwieten L (2022) Multifunctional applications of biochar beyond carbon storage. Int Mater Rev 67:150–200. https://doi.org/10.1080/09506608.2021.1922047

Buford MA, Neary DG (2010) Sustainable biofuels from forests: meeting the challenge. Ecological Society of America

Campbell RM, Anderson NM, Daugaard DE, Naughton HT (2018) Financial viability of biofuel and biochar production from forest biomass in the

face of market price volatility and uncertainty. Appl Energy 230:330–343. https://doi.org/10.1016/j.apenergy.2018.08.085
CRC, c. 666 (2023) Consolidation fertilizers regulations
Finkral AJ, Evans AM, Sorensen CD, Affleck DLR (2012) Estimating consumption and remaining carbon in burned slash piles. Can J for Res 42:1744–1749. https://doi.org/10.1139/x2012-112
Floress K, Cohen A (2022) Pandemic-era Participation in Public Lands Governance: Lessons From the USDA Forest Service. Front Sustain Cities 4
Galinato SP, Yoder JK, Granatstein D (2011) The economic value of biochar in crop production and carbon sequestration. Energy Policy 39:6344–6350. https://doi.org/10.1016/j.enpol.2011.07.035
Han H-S, Jacobson A, Bilek ET, Sessions J (2018) Waste to wisdom: utilizing forest residues for the production of bioenergy and biobased products. Appl Eng Agric 34:5–10
Jang W, Page-Dumroese DS, Han H-S (2017) Comparison of heat transfer and soil impacts of air curtain burner burning and slash pile burning. Forests 8:297. https://doi.org/10.3390/f8080297
Korb JE, Johnson NC, Covington WW (2004) Slash pile burning effects on soil biotic and chemical properties and plant establishment: recommendations for amelioration. Restor Ecol 12:52–62. https://doi.org/10.1111/j.1061-2971.2004.00304.x
Lee E, Han H-S (2017) Air curtain burners: a tool for disposal of forest residues. Forests 8:296. https://doi.org/10.3390/f8080296
Lehmann J, Cowie A, Masiello CA, Kammann C, Woolf D, Amonette JE, Cayuela ML, Camps-Arbestain M, Whitman T (2021) Biochar in climate change mitigation. Nat Geosci 14:883–892. https://doi.org/10.1038/s41561-021-00852-8
Li Y, Hu S, Chen J, Müller K, Li Y, Fu W, Lin Z, Wang H (2018) Effects of biochar application in forest ecosystems on soil properties and greenhouse gas emissions: a review. J Soils Sediments 18:546–563. https://doi.org/10.1007/s11368-017-1906-y
Pachauri RK, Allen MR, Barros VR, Broome J, Cramer W, Christ R, Church JA, Clarke L, Dahe Q, Dasgupta P, Dubash NK, Edenhofer O, Elgizouli I, Field CB, Forster P, Friedlingstein P, Fuglestvedt J, Gomez-Echeverri L, Hallegatte S, Hegerl G, Howden M, Jiang K, Jimenez Cisneroz B, Kattsov V, Lee H, Mach KJ, Marotzke J, Mastrandrea MD, Meyer L, Minx J, Mulugetta Y, O'Brien K, Oppenheimer M, Pereira JJ, Pichs-Madruga R, Plattner G-K, Pörtner H-O, Power SB, Preston B, Ravindranath NH, Reisinger A, Riahi K, Rusticucci M, Scholes R, Seyboth K, Sokona Y, Stavins R, Stocker TF, Tschakert P, van Vuuren D, van Ypserle J-P (2014) Climate Change 2014 Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva
Page-Dumroese DS, Busse MD, Archuleta JG, McAvoy D, Roussel E (2017) Methods to reduce forest residue volume after timber harvesting and produce black carbon. Scientifica 2017:e2745764. https://doi.org/10.1155/2017/2745764
Page-Dumroese DS, Coleman MD, Thomas SC (2016) Opportunities and uses of biochar on forest sites in North America. In: Biochar: a regional supply chain approach in view of mitigating climate change. pp 315–336
Rodriguez-Franco C, Page-Dumroese DS (2021) Woody biochar potential for abandoned mine land restoration in the U.S.: a review. Biochar 3:7–22. https://doi.org/10.1007/s42773-020-00074-y
US Forest Service (2022) Confronting the wildfire crisis: a strategy for protecting communities and improving resilience in America's forests
Wang J, Xiong Z, Kuzyakov Y (2016) Biochar stability in soil: meta-analysis of decomposition and priming effects. GCB Bioenergy 8:512–523. https://doi.org/10.1111/gcbb.12266
Woolf D, Amonette JE, Street-Perrott FA, Lehmann J, Joseph S (2010) Sustainable biochar to mitigate global climate change. Nat Commun 1:56. https://doi.org/10.1038/ncomms1053
Zhang X, Wang H, He L, Lu K, Sarmah A, Li J, Bolan NS, Pei J, Huang H (2013) Using biochar for remediation of soils contaminated with heavy metals and organic pollutants. Environ Sci Pollut Res 20:8472–8483. https://doi.org/10.1007/s11356-013-1659-0