Chipping, Mastication, and Mulching as Fuel Management Methods in British Columbia: A Literature Review

Prepared for BC Wildfire Service and FPInnovations

Shifting Mosaics Corporation
Fort Nelson, BC, Canada
May 2 2024

Acknowledgements

The Shifting Mosaics Corporation team is located throughout Canada and the United States, where our team members live, work, and thrive on lands shared with Indigenous Communities. We acknowledge and are grateful for the collaborative stewardship of all important lands and waters across North America as we all work together for the betterment of the current and next seven generations.

The project team, consisting of Steven Hvenegaard (FPInnovations), Pete Laing, RFT (BC Wildfire Service), Kara Froese (BC Wildfire Service), and Morgan Boghean, RFT (BC Wildfire Service), has been instrumental in guiding the entirety of this project. Their intrigue, direction, support, and countless hours of proactive feedback have resulted in the successful completion of this document.

We extend our gratitude for the time that many have provided us with in discussion, deliberation, expertise, and guidance in the development of this literature review, including Dr. Marty Alexander, Byron Gagne, Ryan Hall, Brad Martin, and Colin Vandergaag.

The authors of this document would like to thank Anne Godlewski for her thorough review in editing this document. Her time and skill set greatly improved this work.

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Caveat

We recommend reviewing this document with those who currently conduct projects related to mastication, mulching, and chipping across British Columbia as their expertise and lessons learned can provide critical feedback and knowledge. These lived experiences, operational complexities, and knowledge across BC will contribute to a broader and deeper understanding of how the above listed processes may be used as fuel management methods. The scientific literature in peer-reviewed publications, white papers, and project reports does not necessarily capture the expertise that exists among licensees, forest professionals, wildland fire and fuel professionals, and others involved in fuel management in BC.

Citation

Shifting Mosaics Corporation. 2024. Chipping, mastication, and mulching as fuel management methods in British Columbia: A literature review. Shifting Mosaics Corporation Report 24.01. Shifting Mosaics Corporation, Fort Nelson, British Columbia, Canada. https://shiftingmosaics.com/.

"I certify that the work described herein fulfills the standards expected of a member of the Association of British Columbia Forest Professionals and that I did personally supervise the work."

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1. The Process

Several authors use the terms *mulching*, *mastication*, and *chipping* interchangeably (Battaglia et al. 2010, Frame 2011, Kreye et al. 2014, Schiks and Wotton 2015a, Fornwalt et al. 2017). In some cases, all three terms are used to describe a single fuel management treatment. Thompson et al. (2016) describe mastication as the chipping of whole, live trees to produce mulch. Wilkinson et al. (2018) use the term *mulch* to describe the byproduct of mastication. Therefore, the results from these studies have been sorted under the applicable term headings unless specific information could be isolated for specific processes. Mastication can occur at a coarse or a fine level. In the former, the masticated fuels include many large pieces where trees are sectioned into lengths of approximately 0.5 m, and in the latter, the fuelbed is dominated by relatively even, fine fuels (Lyon et al. 2018). Fine-level treatments tend to cost more and take longer than coarse-level treatments (Lyon et al. 2018).

1.a. Equipment Used

1.a.i. Treatment process

Chipping

Battaglia et al. (2010) used mulching to describe both mastication and chipping processes. They used a Morbark chipper on two study sites. This chipper is commonly used in chipping treatments that require felled trees and other material to be fed directly into the machine. Fornwalt et al. (2017) also used a Morbark chipper in their mulching study.

Marshall et al. (2008) mentioned the use of cut-to-length harvesters in chipping operations that provide small stems and branches to the chippers. They also noted a trade-off with oil prices, stating that as oil prices rise, the demand for wood chips increases, but so does the price of diesel, which then limits the hauling distance (Marshall et al. 2008). Chippers are suited for producing pulp-quality chips from softwoods. Certain hardwoods can be chipped but may incur additional costs because chipper teeth are quickly worn down. Marshall et al. (2008) therefore recommend investigating the softwood-to-hardwood ratio before performing any chipping treatments.

Multiple pieces of equipment are often needed in chipping operations. Marshall et al. (2008) referenced a case in which a Timbco T-415C harvester was used to delimb commercial stems (≥10 cm diameter) and cut them to 20 ft. lengths. Pre-commercial stems (1.3–10 cm in diameter) were cut and piled separately. The commercial stems were then brought to a small Bandit 1850 chipper by a Fabtek 546B forwarder, and the chips were fed into a trailer for transport. In another study, a Hydro-Ax 670 feller-buncher cut stems that were brought to a landing by a John Deere 648 G-III grapple skidder, delivered to a Prentice 210D loader, and then fed into a 450 HP three-knife Precision 1858 chipper (Mitchell and Gallagher 2007).

Allen et al. (2013) used hand felling and a Vermeer chipper in one of their treatment sites in Cranbrook, BC. Little information was provided on the specific treatment used, but the images in Figure 10 (not shown) of the report show a relatively clean site compared to the dense pre-treatment stand. Chip pieces appear small and similarly shaped, and a visual estimate of depth was provided as an image in Figure 11 (not shown) (Allen et al. 2013).

Hvenegaard (2013) described a chipping treatment performed using a grinder on BC Hydro rights-of-way (ROWs). Dozers were used to spread the chips and then mix them with mineral soil, resulting in chips compacted to a depth of 50 cm. Sparks et al. (2017) used a CAT 320B excavator with a boom-mounted brushing head to chip shrubs remaining in the understorey after thinning the surrounding ponderosa pine (*Pinus ponderosa)* forest.

Spencer and Röser (2017) compiled a report with guidelines on extracting low-quality fibre from forests in BC. Microchippers produce a small chip that is used to produce wood pellets. These chips dry quickly and can be blown into the back of a truck. These machines are available with wheels or tracks. Delimber-debarker chippers can debark wood to ensure a higher-quality chip; however, the wood must be at least 3 m long for the machines to work effectively. Drum-style chippers chip smaller pieces of wood, but they create lower-quality chips because the bark is not removed. For all chipper types, it is important to prevent rocks and sand from being deposited into the machinery to avoid damaging them.

The California Department of Forestry and Fire Protection wrote a Fuels Reduction Guide (CAL FIRE n.d.). After hand or mechanical thinning, they used two types of chipping equipment to change the size, shape, and distribution of forest fuels. For roadside clearing or in residential neighbourhoods, they used towed chipping units. Materials to be chipped were brought to the tow chipper on the road. For off-road sites or steep or difficult terrain, tracked chippers were used. Tracked chippers can be moved by remote control.

Walker et al. (2012) studied the impact and interaction of thinning, chipping, and prescribed fire with understorey shrubs and other plants in mixed conifer forests in the Sierra Nevada. After thinning, slash was masticated and redistributed using a Morbark 30/36 Mountain Goat self-propelled chipper.

Windell and Bradshaw (2000) reviewed forestry equipment used in mastication treatments in the US, including chipping and tree crushing. The equipment catalogue describes self-propelled, whole-tree chippers that chop trees at the stump. However, a separate machine must cut the trees first. The costs of specialized chipping machines and the numbers available were concerning when the authors published this catalogue. The authors reported that the Plumas National Forest managers were interested in a feller-buncher working ahead of the Morbark Mountain Goat chipper, but concerns about the availability and dependability of the self-propelled, whole-tree chipper did not make the approach ideal. The authors also reported on a chipping project near a campground in the Dixie National Forest when prescribed fire was not an option. In this example, chipping operations were very costly.

Fettig et al. (2006) studied chipping operations in Arizona and California to assess the interactions with bark beetle attacks. In this study, all sub- and unmerchantable trees were cut into short lengths and manually fed through a 30.5 cm (maximum-diameter material) chipper. The chipper used was a Model 17 from Wood/Chuck Chipper Corporation. It was moved throughout the treatment unit to facilitate chipping.

Blackburn and Keddy (2018) evaluated bales made from chipped residue by the Gyro-Trac biomass baling system. This could be an option to trial in suitable terrain in BC.

Mulching

Brockway et al. (2009) described mulching as the grinding of trees of all sizes by machines equipped with front-mounted rotary drums and cutting teeth that create wood chips. In their study, the authors mulched hardwood trees of all sizes and all loblolly pines (*Pinus taeda*) less than 20 cm in diameter using a rubber-tired 500 HP Magnum mulcher. However, the mulcher experienced issues on wetter sites, forcing the authors to switch to a tracked 500 HP Delta 953C mulcher. Gray and Blackwell (2016) used a small, tracked forwarder in their thin-and-mulch project in Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine stands.

Hvenegaard (2017) used a Gyro-Trac GT-18 mulcher to create a checkerboard of mulched and residual stems in the Canadian Community Boreal FireSmart project in the Northwest Territories. The mulched grid was characterized by 4 m by 6 m strips. This type of treatment is preferrable for homogenous and dense forests that have few predominantly larger or healthier trees, which would lead to a clumping effect of residual trees. Hvenegaard and Hsieh (2017) intended to use a Rayco C130 mulcher but had to swap to a Fecon F140 due to machine issues. The Rayco C130 was equipped with a MultiDAT data logger; however, productivity for the Fecon F140 was not recorded. Both machines were sized properly to perform fuel treatments in dense black spruce (*Picea mariana*) stands. Hvenegaard and Hsieh (2017) noted that the larger CMI Hurricane, which was brought in to assist with the treatment when the Rayco C130 had issues, was too wide and resulted in more damage to residual stems.

Hvenegaard (2019) used a Gyro-Trac 25XP, which is a low-ground-pressure, belted track machine with cleats for use in the snow. It had a TOMA-AX 700HF cutter head that resulted in a 2.2 m wide mulching surface. Moore et al. (2020) performed a subsequent study at the same mulched site and thus listed the same equipment in their methods.

Hvenegaard (2021) provided a synthesis of fuel treatment productivity across Alberta and discussed the increased use of mulchers in fuel treatments at the wildland–urban interface. The increase was attributed to mulchers being easily transportable, having reduced soil impacts compared to wheeled machines, and being usable in the winter. Mulchers combined with horizontal drum heads and excavators with boom-mounted mulchers were both listed as common equipment used in mulching operations in Alberta. The author listed several case studies in which different machines were used and compared the productivity between them. In one case, a medium-sized CMI Hurricane C250 was used in a mixedwood stand and a smaller Lamtrac 6125T was used where black spruce dominated. A Volvo MCT 135C skid steer loader and a Caterpillar 305.5D mini excavator were subsequently used on both sites to clear additional material and remove snags after the initial mulch treatment. In another study reported by Hvenegaard (2021), treatments in another mixedwood stand were conducted using a Lamtrac 8300T mulcher with an FAE 200/U-225 mulcher head. When the machines were compared, the Lamtrac 8300T appeared to have a higher productivity rate than the CMI Hurricane C250, but the author explained that other factors, such as machine condition and operator skill, contributed to these initial findings. Another machine mentioned was the Lamtrac 8290Q quad-track mulcher, which was used in willow (*Salix spp.*) and open meadows and forested woody debris (Hvenegaard 2021).

Marshall et al. (2008) outlined mulching equipment as having either vertical shaft (mowers) or horizontal shaft (downward grind) heads mounted on rubber-tracked machines with 90–100 HP or on larger pieces of equipment with 400 HP grinders. The authors mentioned that the heavier-duty machines with vertical shaft mowers are better suited to small fuels that are easy to push over, whereas front-based cutters should be used where there is woody vegetation in the mid- and understories. In one operation, a rubber-tracked loader (ASV PosiTrack RC-100) with a Fecon 100 HP mulching head was used to cut stems without grinding them to enhance all-terrain vehicular travel to an adjacent block, which was planned for a prescribed fire. A mulcher and a skidder were used in a similar operation elsewhere in the study area, and both produced fractured stem fuelbeds instead of mulch or chips (Marshall et al. 2008). A crawler with a Fecon RT 400 mulching head was used in another project that focused on grinding and mixing material with the top 3 inches of soil. This resulted in a cleaner site but at the cost of reduced productivity (Marshall et al. 2008).

Smidt et al. (2020) used a Caterpillar 586C site prep tractor with an HM825 mulcher head in their experiment that assessed using a mulcher in establishing a fireline. One-pass treatments were conducted under two speed scenarios: slow (0.8 km/hr) and medium (1.2 km/hr). Two-pass treatments were done at a medium speed of 0.6 km/hr. These speeds were controlled by the operator using the hydrostatic control in creep mode at 25% for the slow treatment speed and at 35% for medium. A fast speed of 1.6 km/hr was found to be unachievable under the study field conditions. The authors provided a cost breakdown of purchasing this equipment. They found that the equipment would need to make $106,445/year (USD) over six years (machine life) to balance out. With operator costs ranging from $210/km to $330/km (USD), the production costs for this type of treatment would be between $840/ha and $2200/ha (USD), based on the assessed operating speeds (Smidt et al. 2020).

Hvenegaard and Hsieh (2015) used a horizontal drum mulcher head by FAE, with fixed teeth. The mulcher head had a swath size of 2.75 m. To operate the mulcher head, the authors selected a Lamtrac LTR8290Q that moved on a steel track (specification in document). The machine was used near Hinton, Alberta, to re-treat two previously treated sites. In a treatment area discussed by Allen et al. (2013), a Lamtrac 8290 was used on slopes <20%, and a disc mulcher on an excavator was used where slopes exceeded that threshold. On another site, a John Deere excavator with a mulching blade and a Cat 320 with a 52-inch mulching disc were used, both of which were found to work well on steeper slopes (Allen et al. 2013).

Hvenegaard and Hsieh (2014a) used a Lamtrac 8300T fitted with an FAE 200U/225 horizontal drum head mulcher to thin spruce (*Picea spp.*) dominated stands. In a study analyzing erosion control in post-burned sites, Foltz and Wagenbrenner (2010) used lodgepole pine (*Pinus contorta*) debris that was mulched using a Vermeer horizontal grinder. Cline et al. (2010) looked at the hydrologic impacts of mastication of juniper (*Juniperus spp.*) trees encroaching on sloped grasslands in Utah. The authors applied a tree shredding treatment to the trees using a Tigercat M726E mulcher from Paris, Ontario, on a rubber-tired vehicle.

Mastication

Mastication redistributes canopy and surface fuels into a compact ground layer composed of broken pieces of material using equipment fitted with rotating drums (Schiks and Wotton 2015a). Jain et al. (2018) provided an overview of common equipment used during mastication. The horsepower, wheel type, and general size of the machines vary. The Forestry Mulcher Guide, as referenced in their research, is a valuable source of information regarding machine specifications; however, it is no longer available online (Jain et al. 2018). Given the amount of detail Jain et al. (2018) provide regarding mastication equipment, only general information was referenced. Specific details can be found in the tables created by the authors in this publication. The authors addressed many common questions in the Sidebar sections of the paper. Table 1 in Jain et al. (2018) summarizes the vegetation types, material masticated, and equipment used.

Mastication requires three separate components: a carrier machine, a cutting head, and a cutting head attachment. The cutting head can be attached using a front-end attachment or a swinging boom.

Customization allows for more flexibility in planning mastication treatment (Jain et al. 2018). Carrier machines can include:

- Skid steers
- Tractors/skidders with either hydraulic or power take-off systems
- Excavators

Cutting heads and their attachments can include:

- Vertical shaft – best for shrubs and young trees <8 inches in diameter; these heads produce messy stumps and chunks of shredded biomass.
    - Disc with fixed teeth
    - Swinging blades attached to disc
- Horizontal shaft – suited for larger trees; these heads leave cleaner stumps and smaller chips.
    - Rotor (drum) with fixed teeth
    - Swinging hammers
    - Fixed knives

Specific information for carrier machines and cutting heads can be found in Table 2, Table 3, and Table 4 in Jain et al. (2018). The authors of this literature review highly recommend this paper as foundational literature for those interested in furthering their knowledge about mastication.

Table 1—Mastication studies that noted the machine type throughout the United States, Canada, and Spain between 2005 and 2016.

Vegetation type[a]	Material masticated: life form	Material masticated: Size (*inch*)	Machine[b]	Literature source
		Study Location: California		
Mixed conifer	Trees, shrubs	Unknown	Machine-mounted HS	Bradley et al. 2006
Chaparral	Shrubs	Unknown	Various	Brennan and Keeley 2015
Mixed conifer	Trees, shrubs	Unknown	Not specified	Burnett et al. 2014
Mixed conifer	Trees	Unknown	Excavator w/ HS fixed teeth	Hatchett et al. 2006
Mixed conifer	Slash	Unknown	Chipper	Johnson et al. 2014
Mixed conifer	Trees	<9	Not specified	Kobziar et al. 2009
PP	Conifers, hardwood	<1	Excavator boom mounted VS	Reiner et al. 2009
Mixed conifer	Trees, hardwoods	1 to 10	Excavator-mounted HS	Stephens and Moghaddas 2005
Shrub	Slash	Unknown	Excavator-mounted HS	Vitorelo 2011
		Study Location: California and Colorado		
P-J, PP	Not described	Unknown	VS knife	Hood and Wu 2006
		Study Location: California and Oregon		
Mixed hardwood	Hardwoods, shrubs	Unknown	Excavator w/ VS, w/ HS, machine w/ VS knife	Kane et al. 2009
		Study Location: Colorado		
P-J, PP, LP	Not described	Unknown	HS hammers, VS knife	Battaglia et al. 2010
P-J	Trees, Shrubs	Variable	Machine mounted w/ swinging knives	Gottfried and Overby 2011
PP	Trees	≤6	Chipper	Wolk and Rocca 2009
		Study Location: Florida		
Longleaf pine, slash pine	Shrubs, saw palmetto, trees	<8	Excavator w/ HS	Kreye 2012
		Study Location: Georgia		
Loblolly pine, hardwoods	Trees	hardwoods; pines <8	Mulcher	Brockway et al. 2009
		Study Location: South Carolina		
Loblolly pine	Hardwoods, shrubs	Down fuels	Chipper	Glitzenstein et al. 2016
Loblolly pine	Beetle-killed trees	Unknown	Excavator w/ HS	Stottlemyer et al. 2015
		Study Location: Texas		
Oak, juniper	All vegetation	<6	HS hammer	Reemts and Cimprich 2014
		Study Location: Utah		
P-J	Trees	Unknown	HS	McIver et al. 2010
P-J	Trees	Unknown	Machine w/ HS (brush cutter)	Moss et al. 2012
P-J	Unknown	Unknown	HS fixed teeth	Roundy et al. 2014
		Study Location: Alberta, Canada		
LP, spruce	Understory trees, shrubs	Unknown	HS fixed teeth	Schiks et al. 2015
		Study Location: Santander, Spain		
Gorse shrubland	All vegetation	Unknown	Excavator w/ HS fixed teeth	Fernandez and Vega 2016

[a] PP = ponderosa pine (*Pinus ponderosa*), P-J = pinyon pine (*Pinus edulis*)/juniper (*Juniperus* sp.), LP = lodgepole pine (*Pinus contorta*), longleaf pine (*Pinus palustris*), slash pine (*Pinus elliottii*), saw palmetto (*Serenoa repens*), loblolly pine (*Pinus taeda*), white fir (*Abies concolor*), oak (*Quercus* sp), spruce (*Picea* sp.), gorse (*Ulex* sp.).
[b] VS = vertical shaft; HS = horizontal shaft.

Table 1. Machine type (Table 1 from Jain et al. [2018]).

Table 2—Size variations in carrier machines. The *Forestry Mulcher Guide* (Catalytic Response, LLC. 2017) identified 79 different carrier machines that have tracks and 30 carrier machines that have wheels. Units are presented in inches (in), pounds (lb) and horsepower (hp).

Specification	**Minimum**	**Median**	**Mean**	**Maximum**	**Number of observations**
	- - - - - - - - - - Tracked carrier vehicles with cutting head attached- - - - - - -				
Power (hp)	99	290	326	765	77
Length (in)	166	242	251	410	55
Height (in)	96	113	114	135	56
Width (in)	59	98	95	132	73
Ground clearance (in)	13	18	18	26	43
Weight (lb)	13,500	26,500	30,597	62,800	57
	- - - - - - - Wheeled carrier vehicles with cutting head attached- - - - - - - -				
Power (hp)	160	245	279	500	29
Length (in)	247	294	292	358	9
Height (in)	112	120	121	130	7
Width (in)	80	106	105	126	30
Ground clearance (in)	19	20	20	21	4
Weight (lb)	16,100	26,600	26,861	38,000	11

Table 2. Machine size (Table 2 from Jain et al. [2018]).

Table 3—Characteristics of the vertical and horizontal-shaft brush-cutting heads (from Coulter et al. 2002; Forest and Rangelands 2015; McKenzie and Makel 1991; Rummer 2009; Vitorelo et al. 2009; Windell and Bradshaw 2000,).

Vertical-shaft	**Horizontal-shaft**
- - - - - - - - - - - - - - - - - - - Head and cutting attachments- - - - - - - - - - - - - - - - - - -	
Cutting devices are attached to a disk or robust mowers	Cutting devices attached to a horizontal shaft or drum
Fixed teeth or blade (mower type)	Fixed teeth, swinging hammers, or ax/knife blade
Boom or front end mounted	Boom or front end mounted
- Vegetation best suited to treat- - - - - - - - - - - - - - - - - - -	
Slash and shrubs Trees 6 to 8 inch diameter when boom mounted	Slash, shrubs when front end mounted Trees up to 30 inches diameter when boom mounted
- - - - - - - - - - - - - - - - - Piece size and posttreatment condition- - - - - - - - - - - - - - -	
Creates large pieces (chunks or shredded) Leaves ragged stumps	Creates small pieces Leaves clean cut stumps
- Carrier machines- -	
Excavator, skid steer, tractors (hydraulic and power take-off)	Excavator, skid steer, tractors (hydraulic and power take-off)
- Microtopography- -	
Broken or dissected topography with a diversity of slope angles and aspects	Continuous and similar slope angle and aspect

Table 3. Vertical vs. horizontal shaft (Table 3 from Jain et al. [2018]).

Table 4—Size variations for masticator heads. The *Forestry Mulcher Guide* (Catalytic Response, LLC. 2017) summarized masticator head sizes for each type of carrier machine. The units are inches (*in*), pounds (*lb*), gallons per minute (*gpm*), and horsepower (*hp*).

Description	Minimum	Median	Mean	Maximum	Number of models
-Masticator heads for excavators-					
Total width (in) (cm)	33	62 (157)	64 (162)	102 (258)	147
Working width (in)	20 (50)	49 (124)	50 (128)	91 (230)	254
Weight (lb) (kg)	320 (145)	2,080 (945)	2,198 (997)	6,803 (3085)	238
Min hydraulic flow (gpm)	4 (16)	30 (114)	30 (115)	74 (280)	201
Max hydraulic flow (gpm) (lpm)	5 (20)	40 (151)	45 (169)	210 (795)	153
-Masticator heads for skid steers-					
Overall width (in)	45 (115)	73 (185)	73 (186)	102 (258)	108
Working width (in) (cm)	36 (91)	60 (152)	61 (153)	83 (211)	115
Weight (lb) (kg)	660 (300)	2,3821,079)	2,171 (984)	3,400 (1,540)	108
Min hydraulic flow (gpm) (lpm)	12 (45)	26 (100)	26 (97)	40 (150)	101
Max hydraulic flow (gpm)	18 (67)	37 (140)	38 (143)	65 (246)	92
-Masticator heads for tractors with hydraulic system-					
Overall width (in)	69 (175)	105 (265)	101 (258)	121 (307)	60
Working width (in) (cm)	58 (147)	89 (2,25)	85 (215)	101 (256)	65
Weight (lb)	1,800 (820)	5,400 (2,449)	5,596 (2,538)	10,800 (4,900)	63
Min hydraulic flow (gpm)	27 (102)	75 (285)	76 (291)	150 (600)	58
Max hydraulic flow (gpm)	45 (170)	120 (454)	122 (463)	210 (795)	56
-Masticator heads for tractors with power take-off system (PTO)-					
Overall Width (in)	51 (129)	93 (236)	92 (233)	138 (350)	270
Working Width (in)	39 (100)	79 (200)	77 (197)	118 (300)	296
Weight (lb)	948 (430)	3,682 (1,670)	4,363 (1,979)	11,757 (5,333)	290
Min PTO power (hp)	55 (41)	105 (78)	141 (104)	295 (218)	32
Max PTO power (hp)	90 (67)	17 (127)	221 (161)	450 (336)	32

Table 4. Masticator head size (Table 4 from Jain et al. [2018]).

Keane et al. (2018) provided similar lists of equipment and characteristics of vertical and horizontal shaft brush-cutting heads (Table 1 in Keane et al. 2018). The sites sampled in their study were masticated using four different pieces of equipment, including a mounted horizontal shaft, a boom-mounted vertical shaft, a chipper, and a mounted vertical shaft (free-swinging cutters) (Keane et al. 2018).

Mitchell and Smidt (2019) mentioned that equipment with fixed teeth can work well in a two-pass system in which masticated material is cut into smaller pieces. The flails and swinging hammers swing back after hitting the ground. This process dulls teeth more quickly and may increase treatment costs as a result (Mitchell and Smidt 2019). Where larger trees are the target for removal, boom-mounted machines with fixed-tooth horizontal shaft cutting mechanisms can cut treetops and masticate the stems vertically to the stump. This type of treatment may result in slower production, given the tree size, and it may be better suited for meeting specific management objectives. The authors added that machine width and cutting head selection may impact manoeuvrability in stands, which influences the resulting stand structure (Mitchell and Smidt 2019).

Kobziar et al. (2013) described mastication as a mowing process that shreds or chips shrubs and small trees using front-end or boom-mounted machinery attached to tracked or rubber-tired equipment (such as a Gyro-Trac). The hydraulically controlled mastication head typically contains rotating blades or a cylinder with cutters that can target understorey vegetation, with minimal impacts on soils and overstorey trees (Kobziar et al. 2013).

Battaglia et al. (2010) used a Hydro-Ax with a vertical shaft or rotary axe mower in their mulching treatments. This piece of equipment is often used for mastication as it is a tracked machine with an attached vertical shaft head or a rotary axe mower. Fornwalt et al. (2017) also used a Hydro-Ax to yield similar results to those in Battaglia et al. (2010).

A Takeuchi TB290 compact excavator with a Fecon Bull Hog mastication head was used in a mastication study by Becker and Keefe (2022). The authors used a global navigation satellite system with radio frequency to track operational efficiency during mastication, which provided data on the expected rates and times for treatments. The data could then help managers better understand, predict, and estimate the costs associated with mastication projects.

Sikkink et al. (2017) and Heinsch et al. (2018) studied masticated sites in mixed conifer stands that were treated using either a vertical rotating shaft cutting head (fixed teeth), a horizontal drum head (fixed teeth), a mowing horizontal shaft (swinging knives), or a chipping head. Brennan and Keeley (2017) focused on vegetation response to mastication treatments in chaparral shrublands. Various mastication equipment was used, but no specific names or brands were given. Schiks et al. (2015) used a Fecon FTX 250 SLGP masticator in their study.

Morgan et al. (2018a) studied fire behaviour in masticated fuels of two different fuel sizes (coarse and fine). The treatments were applied to a ponderosa pine stand using a boom-mounted brushing head attached to a CAT 320B excavator. The fine treatments removed tops that were then ground slowly; in the coarse treatments, trees were cut into 0.5 m lengths (Morgan et al. 2018a). The results showed no difference in fire behaviour between the two treatments; however, the coarse treatment was $471/ha cheaper (Morgan et al. 2018a).

Allen et al. (2013) presented several cases in which mastication treatments were performed near Cranbrook, BC. The field team visited sites treated using a Slashbuster head mounted on an excavator that felled and bucked stems, which were then masticated by a rubber-tired Hydro-Ax. On another site, a Cat 262c skid steer with a horizontal drum was used to masticate standing trees. A Lamtrac LTR 8290 prime mover with a front-mounted FAE drum mastication head (2.5 m cutting width, with 54 replaceable teeth) was used on steeper slopes. On a site near the Kootenays, a feller-buncher with a toothed wheel grinding disc was used on standing trees. An image of the masticated fuel is provided in Figure 33 in Allen et al. (2013), showing larger, unevenly sized intact and fragmented pieces.

Gray (2011) used two different pieces of equipment for masticating fuels in a mixed-species forest in Cranbrook, BC. The equipment included a Slashbuster head mounted on a tracked machine (excavator) and a rubber-tired Hydro-Ax. The excavator with the Slashbuster head targets larger-diameter trees, while the Hydro-Ax is better suited for mowing regeneration patches and shrubs. The trees targeted in

Gray (2011) were <20 cm in diameter. The Slashbuster was used to grab larger-diameter trees and mulch them, while the Hydro-Ax followed to pulverize the residual surface fuels and regeneration patches. These treatments achieved the goal of producing small-particle size to enable rapid decomposition and ease potential wildfire suppression.

Harrod et al. (2009) created a guide for selecting mastication equipment. The authors stated that choosing the right equipment should depend on the desired density of the residual stand. For most types of equipment, targeting tall trees with a large diameter (diameter at breast height [DBH] >9 cm) is not optimal and will increase the costs and processing time substantially. To mitigate this in stands in which taller, larger trees are targeted for removal, the trees could be felled and bucked before mastication. An additional consideration regarding the residual stand relates to spacing. The residual stand needs a minimum 7 m by 7 m spacing to accommodate most common mastication equipment.

Harrod et al. (2009) described the two main types of mastication cutting heads and the advantages and disadvantages of each, as follows:

- Vertical shaft head:
  - Large, heavy discs with hardened steel cutting teeth that spin like a giant lawnmower
  - Requires more machine power to run
  - Often mounted on an excavator boom, allowing the operator to reach up to 9 m in either direction
- Horizontal shaft head:
  - Rotary drum with cutting teeth
  - Requires less machine power to run
  - Can be mounted on an excavator boom, allowing the operator to reach up to 9 m and avoid disturbing soil and manoeuvring challenging equipment
  - Can be mounted directly to the front of a tracked vehicle, which is more efficient for clearing a fireguard than for conducting thinning treatments

The equipment the head is mounted on is important as it can affect the impact on soil and the operational efficiency (Harrod et al. 2009). Self-levelling excavators have better weight distribution and can operate on steeper slopes, with less ground disturbance than conventional equipment.

Clark (2008) compared mulchers with feller/processors to determine which equipment is better for creating firelines. In a comparison test of the equipment, mulchers had a higher utilization rate than feller/processors, but productivity (in square metres per productive machine hour) was variable, with no clear trends between the two. However, the report expressed a preference for using a feller/processor for creating firelines because of the possibility of making money from the felled timber to offset costs, reducing reclamation costs and removing potential fuel load.

The California Department of Forestry and Fire Protection wrote a Fuels Reduction Guide (CAL FIRE n.d.). After hand or mechanical thinning, they used two types of masticating equipment. The first was a skid steer loader with a masticating head. For sites with steep terrain or in areas with larger or heavier fuels (e.g., large brush, trees up to 7.6 m), the equipment of choice was an excavator with a masticator/mulcher attachment. Excavators can have multiple heads, including flat disc or drum heads. Windell and Bradshaw (2000) provided an equipment catalogue for mastication equipment in the US.

They referred to mastication equipment as mechanical brush-cutting equipment and described the advantages and disadvantages of using either vertical or horizontal shafts heads, as follows:

Vertical Shaft Head:

- Advantages
  - Low horsepower requirements
  - Cuts even when dull
  - High kinetic blade energy
  - Low blade life
  - Low energy consumption per tonne of chips produced
- Disadvantages
  - May leave high stubs
  - Small bearing area at blade attachment points, which can accelerate wear
  - Large safety zones required
  - Poor operator visibility
  - Machine may be longer overall

Horizontal Shaft Head:

- Advantages
  - Capable of cutting close to the ground
  - Closer coupled machine
  - Good operator visibility
  - Large blade bearings
  - Both ends of blades are usually supported
  - High kinetic drum energy (flywheel effect)
- Disadvantages
  - Higher power needed to drive cutters
  - Usually, low kinetic blade energy
  - Blades can be difficult to change
  - Poor cutting when the blade is dull (low kinetic blade energy)

Vertical shaft machines are generally considered more productive than horizontal shaft machines. Regardless of the shaft head used, these heads could be mounted on a machine or a boom, or they can be pulled by a machine. For slopes <35%, a tracked excavator with a brush cutter head is recommended. For slopes 50% or slightly greater, a feller-buncher with a self-levelling cab would work better. Depending on the tail swing of the machine, trees designated for treatment may be damaged in the masticating process (Windell and Bradshaw 2000).

Ryans and Cormier (1994) reviewed numerous pieces of equipment used in forestry. They reported that a manager should select a horizontal shaft attachment for finer mulch and easier replanting. If chip size is not a concern, a vertical shaft machine can be used (Ryans and Cormier 1994). The authors stated that some vertical shaft machines can be modified to create finer chips.

Windell and Bradshaw (2000) reported on Slashbuster heads from D&M Machine Division mounted on an excavator for fuel treatments. A Slashbuster has a vertical shaft head with fixed teeth, allowing vegetation to be mulched in place. It can have a large thumb for piling vegetation. The Eldorado National Forest added a modified bar with a cutting surface head to their Slashbuster to masticate smaller standing trees. The Eldorado National Forest indicated that the costs for using this equipment ranged from $220–$270 per acre (0.40 ha), but that a Slashbuster on a feller-buncher with a self-levelling cab was $600 per acre, a significantly higher cost. Windell and Bradshaw (2000) stated that a Slashbuster can be used to create park-like effects through a combination of machine work and successive prescribed fires, but that these results may not be desirable from a cost standpoint.

Jain et al. (2012) reviewed fuel management practices in northwestern US. They found that a horizontal drum masticator was recommended for creating mulch, while a boom-mounted rotary head masticator used to create chunks (>3 in). Hood and Wu (2006) used vertical and horizontal shaft machines for mastication. Vertical shaft hydro-mowers or Hydro-Axs were used most as they were more manoeuvrable on steep slopes and caused less ground disturbance. Kane et al. (2009) reported that all mastication treatments used a front-end or boom-mounted masticator with either a rotating drum or blade-style head. Kane et al. (2010) studied the mastication impacts on understorey vegetation response in a second-growth ponderosa pine forest in the northern Sierra Nevada of California. Mastication targeted shrubs and small trees (i.e., the midstorey) and used a rotary drum–style head with fixed teeth mounted on the front end of a Rayco crawler model #T275. The treatment was completed in May 2002. Cook et al. (2017) conducted a study on sites masticated by a Fecon Bull Hog.

Pile Burning

Hvenegaard and Hsieh (2014c, 2014b) calculated a productivity rate for two different dozers to conduct a blade-and-pile treatment in black spruce stands. A Caterpillar D6N LGP dozer was used with a 4 m straight blade to knock stems down. A Caterpillar D7 dozer equipped with a brush rake was used to conduct the piling. A two-day period of assessment was initially chosen but was increased to five days due to the travel distance. The productivity rate was determined to be 0.69 ha per productive machine hour (Hvenegaard and Hsieh 2014c, 2014b). Hvenegaard and Hsieh (2014b) selected a brush rake attached to a Caterpillar D7G dozer to create windthrows to be burned at a later date.

The California Department of Forestry and Fire Protection wrote a Fuels Reduction Guide (CAL FIRE n.d.). If pile burning is not an option because of weather conditions, the authors propose an alternative of an air curtain burner/incinerator. This equipment creates an almost smokeless burn and emits water vapour and biogenic carbon dioxide but hardly any particulate matter. An air curtain burner can burn 5–7 t of material per hour.

Prescribed Fire

Jain et al. (2012) reviewed fuel management practices in northwestern US. Prescribed fires can be ignited using a hand-held ignition method (drip torch, tiger torch, terra-torch, fusees, matches) or an aerial ignition method (helitorch or plastic sphere dispenser, such as the Red Dragon or Premo).

Raking

Nesmith et al. (2010) used fire rakes and loppers to rake surface fuels 0.5 m away from the base of large trees to protect them from subsequent prescribed fire treatments. Brochez and Leverkus (2022) reported on the use of excavators with modified brush rake attachments for a mechanical raking treatment in northcentral BC in units dominated by lodgepole pine slash.

1.a.ii. Operational limits

Marshall et al. (2008) provided a broad overview of fuel treatments specific to southern US. Several characteristics are associated with mechanical treatments. Where roads do not support the use of larger equipment, either due to lack of width or improper turnarounds or unloading stations, smaller, more manoeuvrable machines should be prioritized. However, there is a trade-off because small equipment has less horsepower and may limit productivity. The authors provided an example of a 100 HP mulching head that could not cut large midstorey trees (>15 cm diameter) and spent more time mulching larger stems that had been felled. When the target fuel reduction is woody vegetation in the midstorey, an important consideration is that vegetation needs to be large and rigid enough to be cut, and residual tree damage must be monitored (Marshall et al. 2008).

Tracked machines are better suited for wet sites with sensitive soils as their weight is distributed more evenly, which can prevent rutting. However, the swivelling motion used for turning tracks can damage roots and boles of trees. Where this is a concern, small, lighter machines should be used despite the associated higher operation costs (Marshall et al. 2008). Slopes >30% limit the feasibility for mechanical treatments, but Marshall et al. (2008) mentioned that the cut-off varies between states in the US, with some restricting harvesting to slopes <40% and others suggesting 25% as the upper limit. The authors also mentioned a case in which a wheeled mulcher experienced issues manoeuvring on clay soils with a 15% slope. The wheeled mulcher had to be replaced with a tracked machine. Mitchell and Smidt (2019) also recommended tracked machines on steeper slopes.

Chipping

Different sized chippers can be used in different stands depending on the target fuel. Small chippers that are fed by hand, such as those used by arboriculturists, are well-suited for small-diameter material to produce chips. For larger stems (5–8 cm in diameter), Marshall et al. (2008) recommend commercial chippers capable of delimbing and debarking trees; however, they are more costly to acquire and difficult to operate.

The economic aspects of chipping revolve around the cost of transporting material to a purchaser and the purchaser's ability to use the material. Chipping operations require a local market willing to use the debris. Stems brought to chippers using skidders must be large enough to be grabbed and chipped, a size that tends to be approximately 7–13 cm in diameter. The costs associated with chipping depend on the market and on the operating costs. Some pre-commercial projects cost $2–$5/acre ($5–$12.50/ha) for the operation and $15–$18/acre ($38–$45/ha) for administrative costs (such as transporting) (Marshall et al. 2008).

Mulching

Brockway et al. (2009) noted that rubber-tired mulchers became bogged down on wet sites, and that tracked mulchers had more advantages operating on slopes and wet areas. Mulching treatments reduced the density of overstorey and midstorey stems ≥5 cm in diameter by 79% and stand basal area by 26%. Removing smaller trees yielded a 128% increase in residual stand diameter (Brockway et al. 2009).

Marshall et al. (2008) noted mulching costs as ranging from $200–$650/acre ($494–$1605/ha). Wheeled machines cost about $258/acre ($637/ha), and tracked machines cost around $171/acre ($422/ha) in flat areas and up to $650/acre ($1605/ha) on slopes (Marshall et al. 2008).

In a study by Smidt et al. (2020), mulcher teeth had an average depth of 71.9 mm and experienced average wear of 3.7 mm throughout the treatment (about 17 hours, including delay times). The authors developed an equation to calculate the expected wear on teeth (W = h/mm) based on tooth dimension (T = mm) and operating hours, finding that a decrease in tooth size from 72 mm to 61 mm would take about 130 hours. A decrease from 72 mm to 51 mm, at which point the shape of the tooth begins to change drastically, could take approximately 370 hours. Additionally, the authors found that mulching in thinned stands made operations more difficult based on manoeuvrability limitations and reduced production speed.

When aiming for stem spacing of 3 m, Hvenegaard and Hsieh (2017) recommended smaller machines (such as the Rayco C130 or Fecon 140 mulchers). The authors noted that larger mulchers (CMI Hurricane) result in stem spacing of 4–6 m. The Rayco C130 engine overheated as a result of the unseasonably warm weather during the treatment. Other mulchers used in the study did not overheat. Hvenegaard and Hsieh (2017) noted that some operators prefer mulching in cold weather as stems are shredded more effectively, but further research is required to confirm the specific details. The authors agreed that operating when the ground is frozen, and snow is present can reduce damage to soils and aesthetic quality and better protect the on-site vegetation. Planning mulch routes within stands was recommended to improve productivity and reduce costs (Hvenegaard and Hsieh 2017).

The Lamtrac 8290 used at a mulching treatment site was unable to manoeuvre between trees spaced <2.8 m apart, and it struggled severing larger stems (Allen et al. 2013). Additional bucking was required where trees had been pushed over rather than cut. A skid steer was used in a part of the treatment, but the authors did not relay its use, only that it performed poorly on slopes >20% and trees larger than 15 cm DBH. Both machines were noted to have lost teeth on rocks. On another site, the mulching blade mounted to a John Deere excavator had trouble mulching large, downed stems. However, it worked well on smaller trees (no diameter thresholds were provided) and on steep slopes, could thin dense clumps of trees, and could avoid rocks (Allen et al. 2013).

Mastication

In a study by Becker and Keefe (2022), mastication was used to reduce stand density in a mixed conifer harvested unit. In the treatment, trees less than 18 cm DBH were removed, with the goal of increasing crown base height and opening the stand for residual trees. All dead and downed debris up to 30 cm in diameter was masticated to reduce ladder fuels and crown fire potential. The authors found that the basal area and the amount of downed material and coarse woody debris influenced the production rate. Site-specific factors, such as slope and soil type, may also be contributing factors that influence the production rate, but this requires further study (Becker and Keefe 2022).

Jain et al. (2018) created several decision trees about mastication to assist managers (Figure 1 and Figure 2). The first question accounts for slope: the authors recommended against using equipment on slopes >40% (<35% is optimal for mechanical treatments). Where slopes exceed this threshold, Jain et al. (2020) suggested that prescribed fire or hand treatments be used. If slopes are within an acceptable range, consideration of mastication treatments should focus on sites with slash, a shrubby understorey, or advanced regeneration with >100 stems per acre (approx. 250 stems per hectare) (Jain et al. 2020). Soil compaction is an important factor to consider (Figure 3). Different equipment specifications might be considered where compaction is an issue (Jain et al. 2020). In their report, Jain et al. (2020) included a brief interview with an operator who cautioned against mulching material >6 inches (15 cm) DBH as doing so would not be cost-effective and has been found to reduce production rate. The interviewee also mentioned that it is important to ensure that operators have the necessary skill for the prescribed treatment. Managers need to determine and demonstrate what 100% productivity looks like and instruct operators to meet a minimum of 80–85% of that target. This allows for sustained production rates and limited residual tree damage (Jain et al. 2020). Jain et al. (2020) reiterate that operator skill is the most important factor to consider in mastication projects, regardless of the machine used.

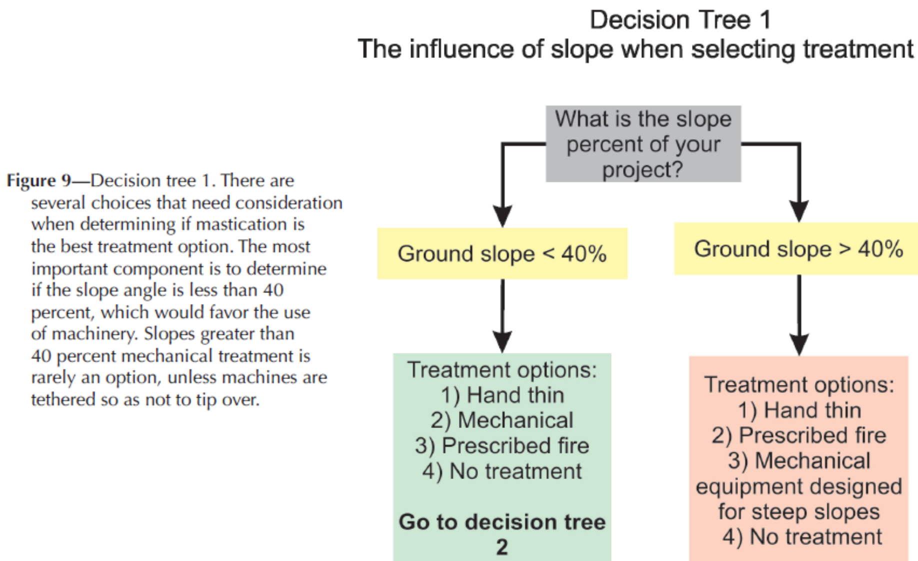


Figure 1. Decision tree for slopes (Figure 9 from Jain et al. [2018]).

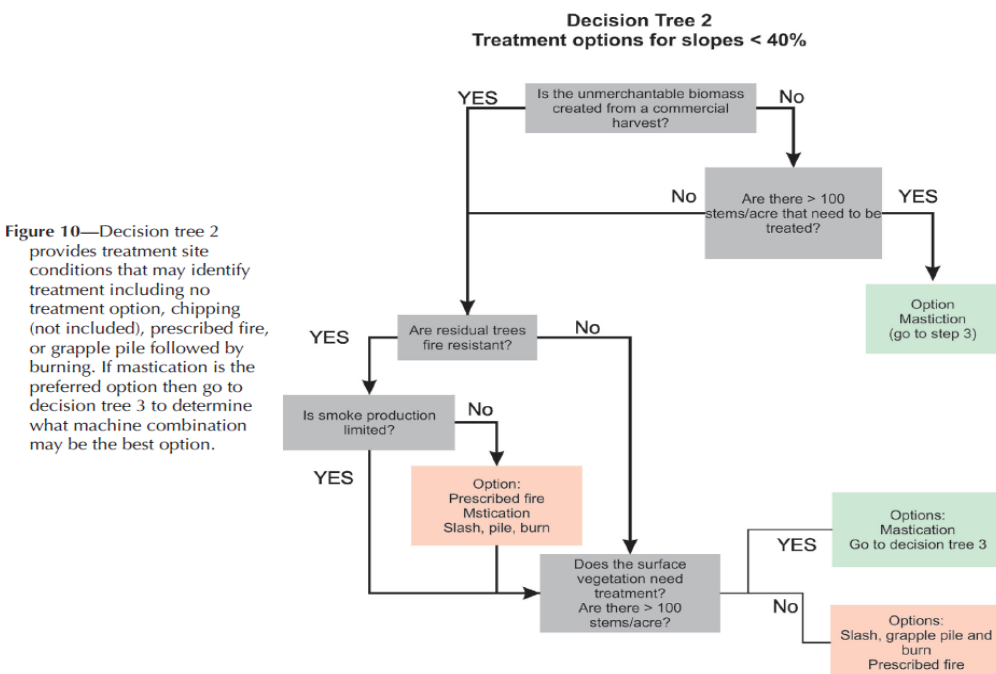


Figure 2. Decision tree for steep slopes (Figure 10 from Jain et al. [2018]).

Figure 11—Decision tree 3 provides the site specific components that may aid in identifying the best machine and masticator head for the project.

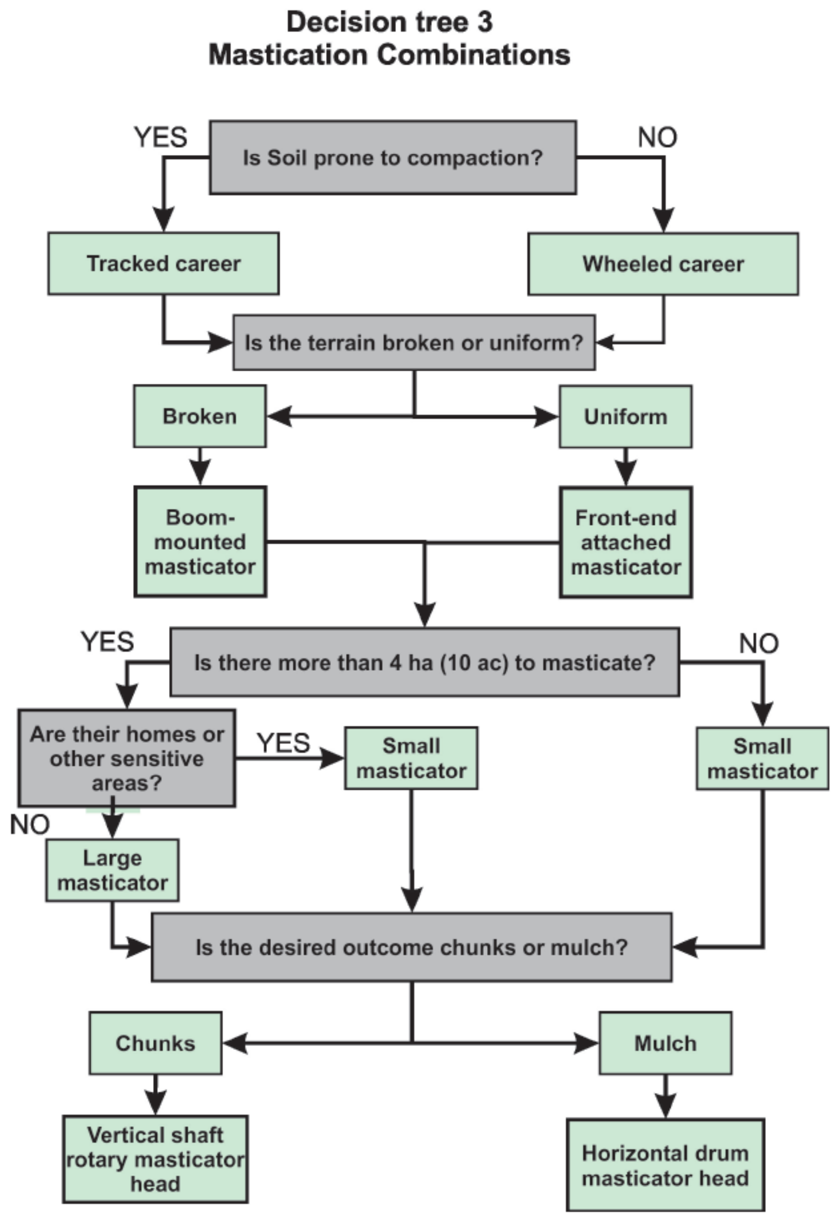


Figure 3. Decision tree for site-specific machinery (Figure 11 from Jain et al. [2018]).

Jain et al. (2018) noted that mastication operations can be expensive as they do not produce merchantable products and are typically conducted in low-value biomass stands. Economic benefits are not usually realized until years later, when residual trees increase in size and become merchantable sawlogs or when wildfire suppression costs are reduced in areas in which a wildfire overlaps with a treatment. The contributing factors for production costs were tree diameter, fuel load, site conditions, and piece size requirements. The authors also provided several tables showing the expected fuel load from treatments (Figures 5, 6, and 7 in Jain et al. 2018, not shown) and from the types of cutting heads (Figure 4) (Jain et al. 2018).

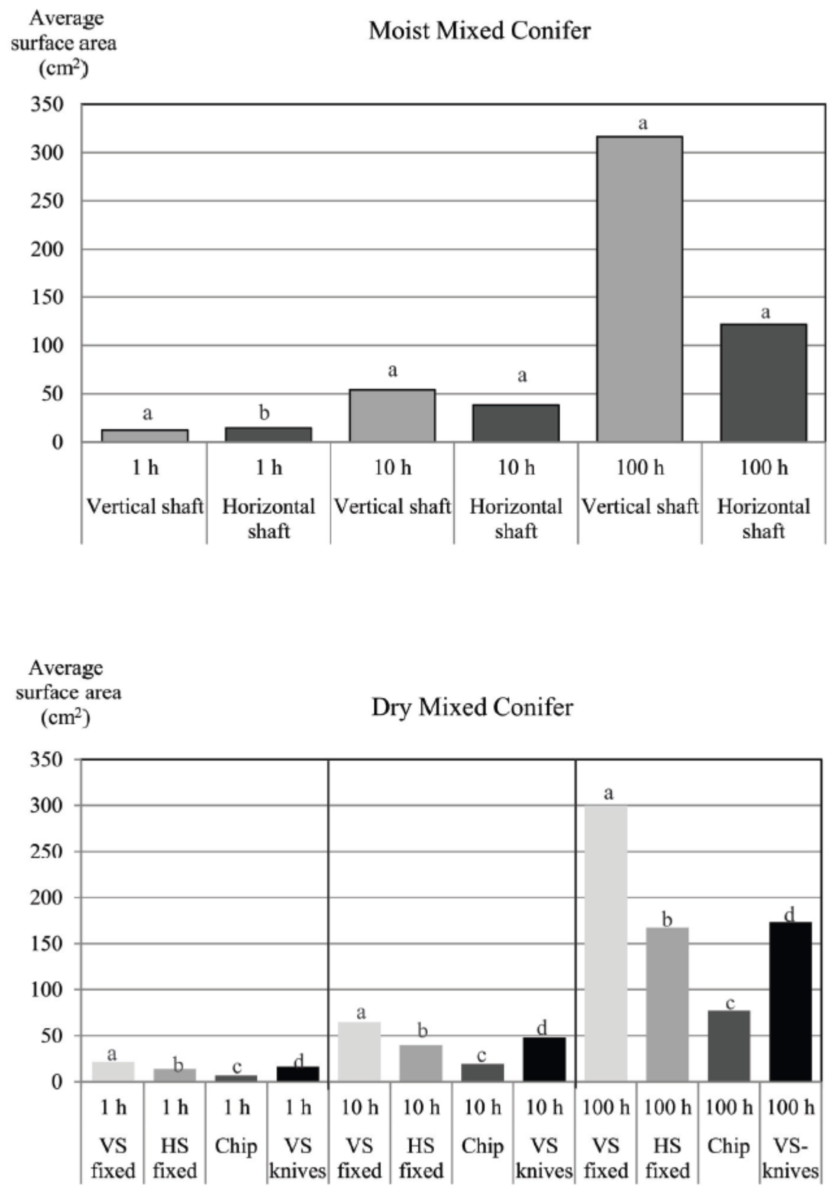


Figure 8—The cutting head designs can result in different piece sizes. Chipping creates the smallest pieces and the vertical shaft cutting head with fixed teeth or swinging knives created the largest pieces (data is from mastodon study (Keane et al. 2018) (Appendix A).

Figure 4. Cutting head influence on chip size (Figure 8 from Jain et al. [2018]).

Allen et al. (2013) noted that a secondary treatment with a Hydro-Ax may not have been needed on top of the Slashbuster mounted head on the excavator. The authors mentioned the need for an experienced operator to minimize damage to residual stems and that the desired piece sizes must be specified. They also found that masticating small-diameter stems was better during cold weather (below –6°C) (Allen et al. 2013).

Harrod et al. (2009) stated that excavators with mounted mastication heads can often reach to a maximum height of only 9 m. Therefore, trees taller than the reach of the equipment may not be appropriate candidates for mastication. Most equipment will have a longer processing time to masticate trees with a diameter >20 cm. Masticating tall, large-diameter trees will also produce substantial surface fuels. Harrod et al. (2009) recommended that tall and large trees be felled and bucked before mastication to avoid lengthy processing times and the high economic costs they incur.

Jain et al. (2012) reviewed fuel management practices in northwestern US. The authors reported that mastication equipment should be used on gentle terrain (slopes less than 35%), as steep terrain creates safety issues for the machine operators, causes greater soil impacts, and increases costs.

Pile Burning

Hvenegaard and Hsieh (2014c) recommended ensuring that all crew members understand the goals and objectives of a project to increase project success. This recommendation was based on an error that occurred during their study. A D6 dozer with a 4 m blade was piling downed stems, instead of the D7 dozer with a brush rake. This error resulted in larger amounts of snow in piled windrows, a situation that could reduce burning effectiveness in the future (Hvenegaard and Hsieh 2014c).

Raking

In a study of sugar pine (*Pinus lambertiana*) mortality in the Sequoia and Kings Canyon National Parks in California, Nesmith et al. (2010) used fire rakes and loppers. They focused on removing surface fuels 0.5 m away from the base of trees ≥10 cm in diameter. Raking was found to be the most effective in sugar pine stands in which levels of forest fuel (litter, duff, and surface debris) had accumulated to at least 15 cm. The mortality rate of trees >50 cm in diameter was better predicted by average duff depth rather than forest fuel depth. This suggests that smouldering and heat retention in duff layers is detrimental to larger trees. Raking around the base of large, merchantable residual trees might be a simple and effective means of increasing survivability of trees in less fire-tolerant stands where prescribed fire is planned. However, the scale of raking is better applied at the site level because hand treatment is time-consuming and can be costly. Additionally, raking was less effective for low- and high-intensity fires. Unless a professional is skilled at moderating fire intensity, this form of raking might be best applied in specific scenarios aimed at protecting residual trees from fire damage (Nesmith et al. 2010).

1.b. Chip Characteristics

The terms used to describe fuel of varying diameter classes varies between counties or regions. In the US, time-lag terms are commonly used to discuss fuels: 1-hour (0.6 cm), 10-hour (0.6–2.5 cm), 100-hour (2.5–7.6 cm), and 1000-hour (7.6–20.3 cm) (Weir 2009). In Canada, the common terms to describe fuels are fine (0–1.0 cm), medium (1.0–7.0 cm), and heavy (greater than 7.0 cm).

1.b.i. Size and shape

Chipping

The woody debris from the Morbark chipper is small and relatively uniform, and has a more limited spread around the chipper (Battaglia et al. 2010). Frame (2011) mentioned that chippers tend to produce more 1-hour (1-h) fuel size classes (>0.6 cm diameter material, or fine fuels). Hvenegaard (2013) found that most of the pieces along chipped ROWs were <1 cm in diameter. Fettig et al. (2006) found the average surface area of the chips created was 10 cm^2.

Blackburn and Keddy (2018) compared chip size between standard mastication/chipping operations and the Gyro-Trac biomass baling system. Chips from the system were 3–13 mm in size, which is much smaller than what standard chipping and mastication methods produce (>32 mm).

Mulching

Frame (2011) noted that the machines used for chipping and mastication (both were described as mulching) left material distributed in a heterogenous manner, leaving some patches of forest floor without any debris and others with thick depths.

In a study by Hvenegaard (2019), mulching was conducted at three intensities to assess operational cost and wildfire behaviour in the resulting fuel load. Low intensity treatments focused on converting standing fuel to surface fuel through minimal mulching that created a coarse fuelbed, more roundwood debris, and undisturbed duff. Mid-intensity (normal) mulching involved knocking over stems and passing over them twice with the machine, resulting in more uniformly chipped material and minimal roundwood left intact. High-intensity mulching differed from normal mulching by purposefully mixing mulched material with duff layers to create a fine fuelbed. Hvenegaard (2019) noted that this treatment intensity is not often used because of the extra costs and operator hesitancy with disturbing duff layers that may damage equipment.

Hvenegaard and Hsieh (2015) found that moisture influenced how much coarse and fine fuel remained after an initial fuel treatment. The amount of fuel left over from the initial treatment impacted the chip size of the re-treatment. Overall, chip size in the re-treatment was variable (Table 5).

Table 1. Dead and down woody debris load (tonnes/ha).

Plot No.	Fine Woody Debris						Coarse Woody Debris
	Size Class 1 (<0.5 cm)	Size Class 2 (0.5-1.0 cm)	Size Class 3 (1.0-3.0 cm)	Size Class 4 (3.0-5.0 cm)	Size Class 5 (5.0-7.0 cm)	Total (<7cm)	(>7cm)
1	0.01	0.15	0.93	2.33	1.61	5.03	8.53
2	0.00	0.02	0.32	1.22	1.51	3.07	16.02

Table 5. Summary of chip size (Table 1 from Hvenegaard and Hsieh [2015]).

Mastication

The Hydro-Ax masticator shreds or grinds woody material into coarse, irregular pieces and can shoot them more than 30 m away (Battaglia et al. 2010). Frame (2011) described the masticated debris as being shredded material typically within the 10-h fuel size class (0.6–2.5 cm diameter, fine to medium fuels).

Kreye et al. (2012) reported that masticated fuelbeds consisted of more than 80% 1-h and 10-h fuels (fine to medium fuels). The authors were interested in piece shape and whether fractured debris underwent moisture loss differently than whole pieces. They found that particle shape had less influence on moisture deposition than fuelbed characteristics, such as depth, bulk density, and fuel distribution.

Schiks and Wotton (2015b) noted that most particles sampled in their study were less than 1 cm in diameter. In another study, Schiks et al. (2015) found that 56% of the masticated pieces were less than 1 cm in diameter and 78% were less than 3 cm. Both studies were conducted on the same research site, with similar tree species composition (lodgepole pine and black spruce).

Mitchell and Smidt (2019) mentioned that a one-pass system of mastication achieves chunky, scattered material. However, where aesthetic quality is a concern, a two-pass system may be needed to create smaller pieces.

Jain et al. (2018) concluded that a vertical shaft cutting head will create larger pieces with more surface area in the 10-h and 100-h fuels (medium fuels) than the horizontal shaft. They mention that where piece size is not a treatment priority, horizontal drum attachments are the most efficient despite creating more 1-h and 10-h fuels (Jain et al. 2018). Jain et al. (2018, 2020) noted that the time spent grinding material dictates the piece size. When more time is spent, the pieces are smaller, and when the operator is processing material quickly, the pieces are larger.

Both the Cat 262c skid steer with a horizontal drum and the Lamtrac LTR 8290 prime mover used in Allen et al. (2013) had issues with tree hinging, which required subsequent cutting (example of hinging shown in Figure 20 of Allen et al. 2013).

Kreye et al. (2014) conducted a literature review on masticated fuels and fire behaviour. They synthesized various fuel loads and sizes that had been reported in other studies (Table 6). Based on their findings, the authors stated that variation in fuelbed characteristics made it difficult to generalize masticated fuels and predict fire behaviour. The only apparent constant was the presence of small-diameter fuels compacted in shallow fuelbeds. The authors noted that the sampling method used may influence the proportion of fuel sizes that are counted, highlighting a study that found more 1-h fuels (fine fuels) counted using plot-based methods and more 10-h fuels measured using planar intercept methods. A hybrid method that uses both fixed area and planar intercept methods was recommended (Kreye et al. 2014).

Kane et al. (2009) reported that mastication altered fuels by changing their shape and size, and the distribution of fuel particle size. The authors illustrated this by reporting the percent of particles that are considered irregular (level of deviation from round). In the 1-h fuel class, 58% were irregular by weight, compared to 51% in 10-h fuels and 35% in 100-h fuels (Kane et al. 2009). Jain et al. (2012) reviewed fuel management practices in northwestern US and found that masticated pieces can be shredded or have angular edges.

Table 1
Masticated surface fuel loadings (Mg ha^{-1}) by fuel bed component for vegetation types studied. Sample techniques include destructive fixed-area and line-intercept (LIS) methods. Data are reported or inferred (indicated by*) from previous research.

Masticated vegetation type (State)	1-h	10-h	100-h	1000-h	Total woody	Litter	Duff	Herbaceous	Total fuel bed	Fuel depth	Woody sample methods
Lodgepole Pine (CO)[a]	16.9	19.3	5.2	5.3	46.7	10.2	11.5	0.2	68.6*	0.6–	1 × 1 m plots for 1, 10, and 100-h.
Mixed Conifer (CO)[a]	23.0	24.5	10.8	5.0	63.4	27.7	19.2	0.1	110.4*	7.3	4 × 50 belt transect for 1000-h.
Ponderosa Pine (CO)[a]	8.0	18.0	7.4	5.3	38.7	13.6	10.5	0.2	63.0*		
Pinyon Pine/Juniper (CO)[a]	7.8	12.0	4.2	3.2	27.2	8.6	4.9	0.4	41.1*		
Loblolly Pine (SC)[b]	2.8	24.1	35.2	127.3	189.4*	5.3	*na*	0.2	194.9*	5.0–15.0	LIS sampling
Shrub-dominated (OR)[c]	12.3	24.6	8.6	5.3	50.7	10.3	6.7	0.0	67.8*	2.9–6.9	0.5 × 0.5 cm plot sampling
Shrub-dominated (CA)[c]	7.6	21.4	8.1	2.2	39.3	8.6	12.4	0.4	60.7*		
Shrub-dominated (CA)[c]	6.2	13.8	3.6	0.0	23.6	2.6	7.5	0.4	34.1*		
Shrub-dominated (CA)[c]	23.5	34.8	5.1	0.0	63.4	0.6	19.6	0.0	83.6*		
Shrub-dominated (CA)[c]	4.7	8.2	1.3	3.1	17.3	2.9	15.0	0.6	35.8*		
Shrub-dominated (CA)[c]	5.2	11.1	6.6	0.0	22.9	5.4	5.7	6.1	40.1*		
Shrub-dominated (CA)[c]	15.7	25.0	4.8	1.3	46.8	9.9	25.9	1.2	83.8*		
Shrub-dominated (CA)[c]	13.2	21.7	2.1	0.0	37.0	5.6	27.9	0.6	71.1*		
Shrub-dominated (CA)[c]	4.4	9.4	1.6	0.0	15.4	4.8	5.9	0.4	26.5*		
Shrub-dominated (CA)[c]	11.8	16.4	3.5	0.0	31.7	3.3	7.0	0.1	42.1*		
Mixed Conifer (ID)[d]	14.9	12.3	11.6	na	na	19.6	na	na	58.4	na	0.37 × 0.37 m plots
Pinyon Pine/Juniper (CO)[e]	na	na	na	na	na	na	na	na	95.9	3.0	Compared 1 × 1 m plot-based methods
Ponderosa Pine/Gambel Oak (CO)[e]	na	na	na	na	na	na	na	na	82.0		to LIS methods.
Jeffery Pine/White Fir (CA)[e]	na	na	na	na	na	na	na	na	73.0		
Ponderosa Pine, 25 yrs old (CA)[f]	0.2	1.4	0.0	57.4	59.0*	2.1	20.4	0.1	81.6*	3.8	1 × 1 m plots
Ponderosa/Jeffrey Pine (CA)[g]	2.9	12.3	12.0	17.9	45.1*	26.1	43.2	na	114.4*	na	LIS sampling
Ponderosa/Jeffery Pine (CA)[g]	1.3	8.3	7.4	32.0	49.0*	19.0	29.1	na	97.1*		
Mixed Conifer (CA)[h]	1.0	4.8	9.0	23.2	38.0*	17.1	32.0	na	87.1*	14.7	LIS sampling
Mixed Conifer (CA)[h]	1.1	4.6	8.7	30.5	44.9*	17.2	31.7	na	93.8*	14.6	
Longleaf Pine/Palmetto-Gallberry Mature 10 + yr rough (FL)[i]	3.1	2.1	0.4	na	5.6*	12.6	41.9	na	60.1*	8.1	1 × 1 m plots; 0.25 × 0.25 m (duff).
Longleaf Pine/Palmetto-Gallberry Mature 10 + yr rough (FL)[i]	3.2	5.3	2.8	1.9	13.2*	9.5	56.5	na	79.2*	5.2	LIS sampling
Longleaf Pine/Palmetto-Gallberry Mature 5 yr rough (FL)[i]	2.3	2.6	0.4	0.6	5.9*	11.8	37.9	na	55.6*	3.5	
Longleaf Pine/Palmetto-Gallberry 18 yr old plantation (FL)[i]	2.7	5.4	1.3	5.1	14.5*	13.6	67.3	na	95.4*	7.3	

[a] Battaglia et al. (2010).
[b] Glitzenstein et al. (2006).
[c] Kane et al. (2009).
[d] Brewer et al. (2013).
[e] Hood and Wu (2006).
[f] Reiner et al. (2009).
[g] Kobziar et al. (2009).
[h] Stephens and Moghaddas (2005).
[i] Kreye (2012).

Table 6. Masticated fuel loading (Table 1 from Kreye et al. [2014]).

Raking

Brochez and Leverkus (2022) found that mechanical raking resulted in reduced fuel load of fine and coarse material. Given that the treatments took place in post-harvest slash, piece size and characteristics were not directly measured. However, the average fuel load varied from 0.79 t/ha to 25.41 t/ha (fine material <7 cm in diameter).

1.c. Chip Bed Characteristics

1.c.i. Depth

Chipping

Hvenegaard (2013) reported a chip depth of 50–70 cm from a chipping operation in the BC Hydro ROW. A year later, Hvenegaard (2014) assessed the area and found that fuelbed depth ranged from 15–30 cm and that chips remained in a continuous layer. Areas with greater fuelbed depth were associated with areas of a larger volume of material processed and where chipping was more intensive (Hvenegaard 2013). The author indicated that standard chipping operations would not produce the greater depths recorded in their study (Hvenegaard 2013). A second chipping treatment resulted in a uniform depth of 50 cm after dozers spread the chips, mixing them with mineral soil (Hvenegaard 2013).

Morrow and Hvenegaard (2016) conducted a study in the BC Northwest Transmission Line ROW that had been chipped. The findings indicated that there was variability in the level of decomposition and regrowth of native and introduced vegetation. Low areas tended to have more moisture, which resulted in a greater rate of decomposition and recolonization of vegetation in areas where the fuelbed was thin enough. The authors also stated that decomposition was accelerated by mixing mineral soil with the chipped debris, which also increased plant establishment. In addition, these areas had less material that remained combustible as only the top few centimetres dried enough to ignite. In areas experiencing large amounts of traffic, decomposition had been accelerated and areas of mineral soil were visible, many of them covered with introduced grasses and clover. Decomposition and plant regeneration were minimal in dry areas (Morrow and Hvenegaard 2016).

Morrow and Hvenegaard (2016) measured moisture at three locations (ROW centre, 1 m from edge, and 3 m from edge) across the BC Northwest Transmission Line ROW. The results showed less difference among sampling location and more difference with depth, in that greater depth generally had more moisture (Table 7).

Table 1. Average moisture profile of chipped fuel beds along the NTL ROW

Year	Sampling depth					
	Surface	5 cm	10 cm	15 cm	20 cm	Bottom
2015	56%	145%	171%	n/a[a]	n/a	n/a
2014[b]	18%	75%	137%	174%	159%	186%
2013[b]	36%	59%	71%	-	81%	70%

[a] *2015 sampling was not conducted at depths greater than10 cm.*

[b] *Data from Hvenegaard, 2014.*

Table 7. Moisture by depth (Table 1 from Morrow and Hvenegaard [2016]).

Mulching

Mulch depth depends on fuel type and the amount being mulched at a site. Mulch may consist of fine and coarse fuels, duff, and soil (Schiks et al. 2016). Schiks et al. (2016) provided a graph of mulch bed thickness as it relates to stand volume and thinning intensity (graph shown in Figure 2 in Schiks et al. 2016). The graph demonstrates that depth increases with increased volume and percent thinning.

Battaglia et al. (2010) found it difficult to distinguish between litter, duff, and fine woody material (<2.54 cm in diameter) when measuring surface fuel load because of the mixing that resulted from the equipment use. The authors combined depth measurements into litter + duff + fine woody debris. These depths were then used to estimate fuelbed loads. The authors also developed a relationship between depth and fuelbed loading for all forest types studied. To best estimate fuelbed load from depth, they recommended conducting 10 samples along a 50 m transect line (Battaglia et al. 2010). Kobziar et al.

(2013) also found a relationship between litter load and depth that demonstrated a sufficient predictor for litter biomass.

Battaglia et al. (2010) conducted a study in dense stands and observed that the average mulch bed depth was variable, ranging from 5.8–7.5 cm. Battaglia et al. (2009) measured the depth required to inhibit understorey regrowth in their study. A chip bed depth of 9 cm and 12 cm inhibited growth in juniper– and ponderosa pine–dominated forests, respectively (Battaglia et al. 2009). Compaction from the previous two to four years after treatment may have reduced the actual depth of the chip bed compared to that which was generated during the treatment (Battaglia et al. 2009). In an erosion control study, Fernández and Vega (2016) dispersed mulch at 87% coverage and 3 cm depth across recently burned soils in Spain. Mulch was not generated from fuel treatments on site but was applied manually and was a byproduct of timber processing.

In a study by Hvenegaard and Price (2018), mulch depth along a fireguard was 9.6 cm, on average. Moore et al. (2020) reported an average mulch depth of 9.5 cm (minimum of 5 cm and maximum of 17 cm). Hvenegaard et al. (2016) found that mulch depth was 2.3 cm in strip mulch sites and 2.1 cm in mulch thinned sites, on average, in a black spruce stand.

Hvenegaard and Hsieh (2015) re-treated a fuel reduction site and found that fuel load and distribution were variable in the previously mulched site. Both fuel load and distribution were influenced by the amount of fuel and whether coarse or fine fuel was left (Table 5). Moisture influenced the amount and type of remaining fuel (Hvenegaard and Hsieh 2015). There is a trade-off between mulch depth and water retention. Thinner mulch layers will likely be wetted across the entire fuelbed profile, whereas thicker layers may remain dry (Frame 2011). The thicker layers may also remain moist longer than thin layers during periods of drought. Mulch depth may depend on site conditions and expected weather patterns, and on management objectives.

Battaglia et al. (2010) found that mulching (here, meaning chipping and/or mastication) increased surface fuel load the most in mixed conifer forest types, followed by lodgepole pine, ponderosa pine, and juniper types. On average, there was a 19–26% increase in total woody fuel load, most of which consisted of fine fuels (1-h and 10-h fuels). Needle litter increased in mulched areas, as did herbaceous fuel load, but the increase in woody debris shifted the fuelbeds to a compact woody/needle classification. The authors found that the fuel components in their mulched sites were highly correlated, suggesting that the mulched fuelbeds differed only in total fuel load between forest types. Mulch depth ranged from 0–9 cm (juniper) forest types) to 0–13 cm (lodgepole and ponderosa pine stands) to 0.5–15 cm (mixed conifer stands).

Mastication

Kobziar et al. (2013) found that mastication depth in a mature, fire-suppressed stand of pine in Florida was 4–8 cm. In an experimental burn over litter and shrub masticated fuelbeds, depths were constructed at 6.1, 8.9, and 11.9 cm (Kreye et al. 2013). Kreye et al. (2012) reported depths of 4.6 to 8 cm in 10 masticated sites in northern California and southern Oregon, mostly consisting of 1-h and 10-h fuels. Wilkinson et al. (2018) reported masticated fuel depth as 4.1 cm, on average, in thinned sites (where all material was masticated), and 3.3 cm, on average, in stripped sites (where 5 m swaths of forest were masticated with natural retention between sites). Schiks and Wotton (2015a) cited an average depth of 11 cm in their study, which was similar to another study by the same authors (Schiks and Wotton 2015b), in which depth was 10.6 cm on average. A literature review by Kreye et al. (2014) found that masticated fuelbed depth was generally shallow, ranging from 0.6–15 cm.

Yukon Wildland Fire Management (2022) reported numerous characteristics of a masticated treatment site (11.2 ha). These included fuel loading of 131.17 t/ha, an average depth of 7.25 cm, and a fuel weight totalling 1,469.05 t (Table 1 in the document [not shown in this report] contains individual measurements). The authors noted that the upper layers of the masticated beds were much drier than most fuel types in the Fire Behaviour Prediction system. This drying was attributed to increased air space and UV radiation. The moisture content of the fuelbed was highly variable, but the lower layers (depths) retained more moisture for long periods after precipitation. Yukon Wildland Fire Management (2022) reported that masticated fuelbeds have high probability of ignition, but fires that do ignite are easily controlled under appropriate fire weather indices (Table 5 in the document [not shown in this report] shows the fire weather indices during the experiment).

Harrod et al. (2009) used a vertical mastication shaft head on a tracked excavator to thin a forest. After this treatment, the average fuelbed depth increased by as much as 5.08 cm. However, the changes in total surface fuel loading varied among fuel size classes and highly depended on the material being masticated.

Sparks et al. (2017) conducted a thinning and chipping treatment, and Lyon et al. (2018) used the same treatments in a follow-up study. Lyon et al. (2018) found that whether chipping was conducted at the fine or the coarse level, the fuel loading and depth of the fuelbed did not differ. The fuel bed depth ranged from 7–14 cm (3–6 in.) and fuel loading ranged from 1.0–16.0 kg/m^2 (1–18 lb./ac.) (Lyon et al. 2018).

Kane et al. (2009) found significant differences between sites for fuelbed depth (Table 8) and bulk density, with depth ranging from 4.6–8.0 cm and bulk density ranging from 45.9–115.3 kg/m^3. When looking at fuel distribution across all sites, most fuels fell into the 10-h class (53%) and 1-h class (29%) of all masticated fuel material. The authors used the planar intercept method to estimate fuel load in sites that had been masticated. Like other estimation techniques, the planar intercept method showed significant variation between sites for all fuel classes (Table 8). The sites varied from 13.4–41.6 Mg/ha in total fuel load (Table 9), and one site had 300% more fuel than the lowest site. Pooling all sites, the 10-h fuels made up the largest proportion of fuel load (51%), followed by 100-h fuels (25%) (Kane et al. 2009).

Kane et al. (2009) reported that masticated fuelbeds had the greatest fuel load in the 1-h and 10-h fuel classes. This fuel load distribution makes masticated fuelbeds unique compared to natural and slash-based fuelbeds. The authors found that masticator type did not impact the amount of fuel in the 10-h fuel class, indicating that other factors may be important in determining chip and fuelbed characteristics.

Table 3. Comparisons of mean surface and ground fuel loading (standard error) for mechanically masticated areas from the plot-based sampling method (50 x 50 cm) by time-lag class and study site (see Table 1)

Live fuels consisted of both herbaceous and woody components. Post-hoc tests were completed with a Kruskal–Wallis multiple-comparison Z-value test and denoted with superscripted letters. Values that share the same letter within each column are not significantly different

Site	*n*	1-h	10-h	100-h	1000-h	Total woody	Live	Litter	Duff
						(Mg ha^{-1})			
APP	15	12.3 (2.8)^{ab}	24.6 (4.9)^{abc}	8.6 (4.9)	5.3 (5.3)	50.7 (10.0)^{ab}	0.0 (0.0)^{c}	10.3 (2.8)^{abc}	6.7 (3.1)^{bc}
CFR	40	7.6 (0.9)^{bc}	21.4 (2.7)^{abc}	8.1 (2.3)	2.2 (1.6)	39.3 (6.1)^{abc}	0.4 (0.3)^{bc}	8.6 (1.1)^{ab}	12.4 (1.8)^{abc}
IMR	15	6.2 (1.7)^{bc}	13.8 (4.0)^{bcd}	3.6 (1.7)	0.0 (0.0)	23.6 (6.9)^{bcd}	0.5 (0.4)^{abc}	2.6 (0.6)^{cd}	7.5 (3.1)^{bc}
MAD	15	23.5 (2.6)^{a}	34.8 (4.3)^{a}	5.1 (2.5)	0.0 (0.0)	63.4 (7.8)^{a}	0.0 (0.0)^{bc}	0.6 (0.3)^{d}	19.6 (4.3)^{ab}
MFR	15	4.7 (1.1)^{bc}	8.2 (2.2)^{cd}	1.3 (0.6)	3.1 (2.2)	17.4 (4.0)^{bd}	0.6 (0.3)^{abc}	2.9 (0.5)^{cd}	15.0 (3.7)^{abc}
SFR	15	5.2 (1.0)^{bc}	11.1 (2.3)^{bcd}	6.6 (2.9)	0.0 (0.0)	22.9 (5.4)^{bcd}	6.1 (2.0)^{a}	5.4 (1.5)^{abc}	5.7 (2.1)^{bc}
STA	15	15.7 (1.7)^{a}	25.0 (3.3)^{ab}	4.8 (1.6)	1.3 (1.3)	46.9 (6.1)^{ac}	1.2 (0.5)^{ab}	9.9 (1.0)^{a}	25.9 (4.0)^{a}
TAY	15	13.2 (2.9)^{ab}	21.7 (4.4)^{abcd}	2.1 (0.8)	0.0 (0.0)	37.0 (6.4)^{abc}	0.6 (0.3)^{abc}	5.6 (1.4)^{abc}	27.9 (5.0)^{a}
WFR	40	4.4 (0.8)^{c}	9.4 (1.7)^{d}	1.6 (0.6)	0.0 (0.0)	15.3 (2.8)^{d}	0.4 (0.2)^{bc}	4.8 (0.5)^{abc}	5.9 (1.2)^{c}
WHI	15	11.8 (2.4)^{ab}	16.4 (2.9)^{abcd}	3.5 (1.5)	0.0 (0.0)	31.8 (5.3)^{abcd}	0.1 (0.1)^{abc}	3.3 (0.7)^{bcd}	7.0 (1.5)^{abc}
P		<0.001	<0.001	0.089	0.264	<0.001	<0.001	<0.001	<0.001
All sites		10.5 (1.9)	18.6 (2.7)	4.5 (0.8)	1.2 (0.6)	34.8 (4.9)	1.0 (0.6)	5.4 (1.0)	13.4 (2.7)

Table 8. Surface and ground fuel loading (Table 3 from Kane et al. [2009]).

Table 4. Mean woody fuel loading estimates by time-lag class based on the planar intercept sampling method for mechanically masticated sites (see Table 1)

Post-hoc tests were completed with a Kruskal–Wallis multiple-comparison Z-value test and denoted with superscripted letters. Values that share the same letter within each column are not significantly different

Site	*n*	1-h	10-h	100-h	1000-h	Total woody
				(Mg ha^{-1})		
APP	15	5.7 (0.9)^{b}	16.8 (2.9)^{abc}	9.2 (2.2)^{abc}	3.1 (1.0)^{b}	34.8 (4.4)^{ab}
CFR	34	1.0 (0.2)^{de}	14.3 (1.5)^{bc}	12.9 (1.3)^{a}	7.0 (1.4)^{ab}	35.3 (3.0)^{ab}
IMR	15	2.2 (0.5)^{cde}	6.1 (1.1)^{d}	4.8 (1.3)^{bcd}	0.3 (0.2)^{cd}	13.4 (2.3)^{c}
MAD	15	4.3 (0.5)^{bc}	30.1 (3.9)^{a}	7.2 (1.7)^{abc}	0.0 (0.0)^{d}	41.6 (4.6)^{a}
MFR	15	2.0 (0.3)^{de}	8.1 (1.5)^{cd}	3.1 (1.2)^{cd}	0.7 (0.4)^{cd}	14.0 (2.7)^{c}
SFR	15	1.0 (0.2)^{de}	8.1 (2.2)^{cd}	7.2 (1.6)^{abc}	16.8 (4.0)^{a}	33.1 (4.5)^{ab}
STA	15	9.8 (1.1)^{a}	21.2 (3.4)^{ab}	8.9 (1.7)^{ab}	1.1 (0.9)^{cd}	41.0 (6.0)^{a}
TAY	15	4.4 (0.5)^{bcd}	15.8 (2.0)^{bc}	8.3 (2.0)^{abc}	8.4 (5.7)^{bcd}	36.8 (6.8)^{ab}
WFR	40	1.6 (0.2)^{de}	10.0 (1.4)^{cd}	1.7 (0.4)^{d}	0.3 (0.2)^{d}	13.6 (1.6)^{c}
WHI	15	2.7 (0.4)^{cde}	10.0 (1.5)^{bcd}	7.6 (1.4)^{abc}	0.0 (0.0)^{d}	20.4 (2.8)^{bc}
P		<0.001	<0.001	<0.001	<0.001	<0.001
All sites		3.5 (0.8)	14.0 (2.3)	7.1 (1.0)	3.8 (1.7)	28.4 (3.5)

Table 9. Fuel loading by time-lag class (Table 4 from Kane et al. [2009]).

Hood and Wu (2006) found an average masticated fuel depth of approximately 3.0 cm for pinyon pine (*Pinus edulis*)–juniper, ponderosa pine–gamble oak (*Quercus gambelii*), and Jeffrey pine (*Pinus jeffreyi*)–white fir (*Abies concolor*) fuel types in Colorado and California. The average depth of surface fuels varied by vegetation and fuel type. The median fuelbed bulk density was 129 kg/m^3 for Jeffrey pine–white fir, 128 kg/m^3 for ponderosa pine–gamble oak, and 226 kg/m^3 for pinyon pine–juniper. For the masticated/woody layer, the bulk density was 155 kg/m^3 for Jeffrey pine–white fir, 156 kg/m^3 for ponderosa pine–gamble oak, and 218 kg/m^3 for pinyon pine–juniper. Some of this variability may be a result of the difficulty in accurately separating individual fuel components during collection (Hood and Wu 2006).

1.c.ii. Continuity

Mulching

Battaglia et al. (2010) reported a decrease of 30–45% in litter and duff cover in their study, due to a significant increase of 30–52% in small woody debris (1-h and 10-h fuels) cover generated by the treatment. The addition of small fuels now covering the forest floor altered the predominant substrate. This finding was not as consistent with areas covered by larger fuels (100-h and 1000-h), where there was increased variability in coverage between the stands. Percent cover in untreated stands was used to estimate 100-h fuel load. There was more variability in smaller-diameter debris load when compared to coarse debris (untreated) areas. The amount of tree biomass that was treated provided a good indicator for the expected needle and woody debris deposition and amount of mulch (litter + duff + 1-h + 10-h) on the forest floor. Mulching treatments showed increased continuity of 1-h and 10-h fuels, which contributed the most to total fuel load (Battaglia et al. 2010).

Battaglia et al. (2009) had similar findings to Frame (2011), in that mulching did not create a homogenous bed of chips; rather, it created a mosaic of coverage ranging from a forest floor with no mulch to areas completely covered by mulch of varying depth. Patchy chip distribution at the landscape level created variable vegetation responses (Frame 2011).

Mastication

Yukon Wildland Fire Management (2022) created a masticated treated research area by harvesting marketable timber and then masticating the remaining timber and evenly spreading the debris.

Pile Burning

In a mechanical raking treatment, Brochez and Leverkus (2022) noted that some debris piles did not burn as well as others due to the excessive mineral soil and organic material added to the piles during fuel treatment. Piles were not directly measured for chip characteristics, but visual assessment noted variable piece size, similar to that in standard slash piles created in harvesting operations (Brochez and Leverkus 2022).

Raking

Brochez and Leverkus (2022) reported on mechanical raking treatment results. Fuelbed continuity after the treatments was sparse due to the treatment fuel targets. This resulted in significant mineral soil exposure and limited continuity between woody pieces.

Fettig et al. (2006) experimented with chipping treatments in ponderosa forests of Arizona and California to determine how they interactions with bark beetles. One set of treatments focused on chipping, followed by raking chips away (2 m distance) from the boles of residual trees.

1.c.iii. Alteration over time

Chipping

In a study by Hvenegaard (2014), a chipped ROW was reassessed a year the 2013 initial assessment. for ignitability and moisture changes. Moisture content was generally higher at lower depths: there was 2.5 to 3 times more moisture at 2 cm than at the surface. Additionally, a year of precipitation contributed to the moisture reservoir within the fuelbed, increasing the moisture content from what was measured in the first year of treatment (Hvenegaard 2014).

In a study conducted on the chipped bed of a BC Hydro Northwest Transmission Line ROW, Morrow and Hvenegaard (2016) reported that decomposition led to a reduced fuel load each year since initial treatment in 2014. Decomposition created favourable conditions for re-establishment of plant species, many of them being low-flammability species that may reduce wildfire. Areas with chip bed depth of less than 8 cm also promoted native plant re-establishment and reduced wildfire potential as the plants cover the chip beds. These trends may not occur in areas of low moisture or precipitation as decomposition would be minimal (Morrow and Hvenegaard 2016).

Uzunovic and Semple (2019) reviewed the current production of wood chips in Canada and the presence of potential international markets for Canadian wood chips. Storing piles of wood chips can be hazardous. The potential for off-gassing of carbon dioxide, carbon monoxide, methane, and heavy aldehydes also exists. However, piles of wood chips can be stacked outside for two to three years, with minimal damage from staining/decay.

FPInnovations (2012) evaluated stored chip (hog fuel) piles and found that as chips become more compacted, air flow decreases, temperature increases, and the chance of fire is reduced. Microbial decomposition can continue with reduced air flow, so material loss will continue.

Mulching

Fornwalt et al. (2017) noted that six to nine years after mulching, the average mulch depth was 2 cm in juniper stands (previously 9 cm after treatment) and 4–5 cm in ponderosa pine, lodgepole pine, and mixed conifer stands (previously 12.5 cm on average after treatment). However, bulk density at these sites was much higher because of compaction.

Rhoades et al. (2012) measured a subset of the sites in Battaglia et al. (2010) three to five years after treatment. They found that 1-h and 10-h fuel cover was five to eight times higher and 100-h fuels were two to four times higher in mulched sites than in untreated areas. The authors found that these fuels were equivalent to 1.6 times the mass and twice the depth of the O horizon in adjacent untreated sites. Herbaceous plant cover remained high (double that of untreated areas), and woody plants declined.

Wolk et al. (2020) noted that masticated fuelbeds that had aged 10–16 years, had increased density of fuelbeds which resulted in longer smouldering times due to denser beds having less oxygen, and the presence of a duff layer beneath the chipped material. Fuelbed density also changed with time; mulched materials lost 50–80% of their mass after six to nine years.

In a follow-up study to Battaglia et al. (2010), Fornwalt et al. (2017) observed that mulch depth had compacted to the extent of 2 cm (0–9 cm total depth after initial treatment) in juniper stands, 4–5 cm (0–13 total depth after initial treatment) in ponderosa pine and lodgepole pine, and (0.5–15 cm in total depth after initial treatment) in mixed conifer stands. The authors also reported a significant increase in understorey vegetation and discussed how desirable increased plant establishment may be depending on the goals for the stand. In areas in which fire was suppressed for long periods, such as ponderosa pine ecosystems, increased growth of understorey vegetation may be encouraged where it was previously missing due to a dense overstorey canopy (Fornwalt et al. 2017).

Mastication
Decomposition rates in masticated sites did not differ between treated and untreated areas, according to a study by Kobziar et al. (2013). They reported that nearly one year after treatment, 74% of litter and 82% of 1-h fuels remained after 10 months and that 81% of 10-h fuels persisted.

Keane et al. (2018) initiated a study called MASTIDON (MASTIcated fuelbed Decomposition Operational Network) to study fire behaviour, moisture dynamics, smouldering, and soil heating in masticated fuelbeds over time. The physical and chemical properties of the fuelbeds were measured such that changes could be documented over 10 years throughout sites across the Rocky Mountains in the US. The authors found few significant differences in the fuelbeds over 10 years, with only nitrogen and cellulose concentrations decreasing and bulk density increasing, though these differences were minor and highly variable. The variability was attributed to study site selection; the authors noted that 11 of the 15 sites were in dry mixed–ponderosa pine stands that experience low precipitation and slower decomposition rates. They also considered that the addition of litter and debris from residual stems over time contributed to the physical and chemical characteristics that were measured. The results suggest that masticated fuelbeds in dry forest types may not experience significant changes until after a decade. This can have management implications, in these dry forests where decomposition is thought to occur readily after treatments (Keane et al. 2018).

Pickering et al. (2022) studied masticated fuelbeds across 53 sites in Australia, including dry forests, lowland forests, woodlands, heathlands, and coastal scrub grasslands. The authors were interested in the effects of time and aridity on the fuel load of masticated beds. Coarse (6-25 mm in diameter) and total fuel load remained constant for up to nine years after mastication, while fine fuel load (<6 mm in diameter) and fuelbed depth decreased with time. Immediately after treatment, fuelbeds were composed of 45–55% coarse fuel particles (similar to some North America studies), and total surface fuel load in masticated sites was 62% higher than in untreated sites. After nine years, coarse fuel made up 75–80% of the total fuel load, likely due to the slower decomposition rate of the larger particles. Total fuel load, coarse fuel load, fine fuel load, and fuelbed depth increased as aridity increased.

Liu et al. (1996) summarized guidelines for storing and disposing of wood residue. Storing wood residue in piles or in a landfill can lead to the formation of methane gas from the biological decomposition of the wood under anaerobic conditions and the formation of carbon dioxide under aerobic conditions. Methane is a fire and explosion hazard, and both methane and carbon dioxide are greenhouse gases that contribute to climate change.

1.d. Utilization of Chipped Product

1.d.i. Methods
A unique and novel approach to chip utilization is occurring in rural Fort Nelson, BC, whereby a landowner is heating his home, and soon his greenhouse and other farm buildings, using a wood biomass–powered boiler system produced by Hargassner https://www.youtube.com/watch?v=UgPh9yNFwP4. This system is fully automated. It can be controlled and monitored using an app on a smartphone. The boiler system can burn sawdust, pellets, and chipped woody biomass. The system is equipped with a chipper and a chip storage bin. Such systems are very efficient and have been used in other countries for decades. They hold potential for many cities and villages that rely on hauling of fuel to heat homes and businesses. As stated by some of the authors cited in this review, there is potential for great benefit for remote and rural communities. The systems could be installed to heat homes and greenhouses, and the

fuel could be supplied through FireSmart practices to protect the communities. These practices could create jobs for local community members.

Blackburn and Keddy (2018) stated that there are many potential uses for the biomass bales produced by the Gyro-Trac biomass baling system (Figure 5). Many of the proposed uses revolve around combined heat and power plants and include feedstock used in direct combustion or gasification to produce heat and/or electricity. The feedstock could also be turned into pellets for use in combined heat and power plants, but they must be dried, and the chip size reduced. The packaging of the bales (Figure 5) makes them easy to transport, which could save on transportation costs, but it also allows them to be sold individually or in any quantity needed. This increases the potential use of the bales in chipmats to reduce rutting in areas of high traffic or as spill kits as the wood is an effective absorber (Blackburn and Keddy 2018).

Figure 1. The Gyro-Trac bioenergy baling system (BBS).

Figure 2. Compact woody biomass bales (1.22 × 1.18 m).

Figure 5. Gyro-Trac system and biomass bales (Figures 1 and 2 from Blackburn and Keddy [2018]).

Spencer and Röser (2017) compiled a report with guidelines on increasing and extracting low-quality fibre from BC forests. Firewood can be created from FireSmart fuel treatments around communities, which can then provide a heat source for residents and protect communities from wildfire.

The California Department of Forestry and Fire Protection wrote a Fuels Reduction Guide (CAL FIRE n.d.). Thinning before conducting other treatments often results in a small number of timber logs that could be economically costly to transport to a sawmill. Bringing a portable sawmill to process these trees on site is a potential compromise. The sawn logs can be used to make picnic tables or other small projects in state parks.

Sikka et al. (2013) studied the feasibility of switching fossil fuel heating to biomass heating in remote Indigenous communities in southeast Alaska by using residues from logging. The authors found that there are many potential economic (lower operational costs than fossil fuels), environmental (lower carbon emissions), and social (potential new jobs) benefits of using logging residue for heating. They noted that 65% of the biomass needed to heat all communities could come from the waste of the existing logging operations in the region.

Coote (2012) wrote a magazine article describing the possibilities of expanding biomass heating systems in Australia using waste wood material. The author stated that wood from sustainable sources is considered a low-carbon, renewable energy, and that many nations in Europe are leading the way with biomass energy. In Australia, possible feedstock could come from timber industry waste, wildfire fuel reduction, firebreaks, or other sources. In many cases, the waste biomass either ends up in landfills or is burned. Another use of this waste could be for offsetting reliance on fossil fuels for heat and energy. Coote (2012) noted that wood energy systems are seen as a key contributor to greenhouse gas mitigation efforts in Europe. The author also noted that decentralized energy systems provide energy and economic resilience, with regional benefits from spending money locally on producing energy versus exporting money to distant energy sources.

De Jong et al. (2020) wrote a follow-up report (original in 2011) on the progress of the biorefinery industry in expanding into biofuel and bioproduct industries. The authors noted that the relatively low price of fossil fuels over the previous decade and the optimized nature of fossil fuel–based production processes have hampered the acceleration of commercial production of bio-based products compared to the projected amount in their bio-based chemicals report from 2011. However, it is estimated that the production of bioproducts, including biofuels, could generate $10 billion (USD) of revenue for the global chemical industry (De Jong et al. 2020). Wood is a second-generation feedstock for biorefineries and can be used to create biofuels, heat and power, and chemicals. De Jong et al. (2020) described actions for policy, technology, feedstock availability, and social acceptance to align with a sustainable development scenario that incorporates the use of biomass and biorefining. Strong forces, such as the desire to mitigate climate change, transition to a circular economy, shifting consumer preferences, new corporate commitments, and government mandates and support, are driving development in biofuels and bioproducts. In the future, the areas that are increasing in the use of biomass, such as woody debris from fuel treatments and biorefining, are food and nutrition, flavours and fragrances, cosmetics and personal care products, pharmaceuticals, fine chemicals, and other chemicals.

1.d.ii. Considerations and barriers

A literature review by Evans et al. (2011) revealed that several forest managers support whole-tree harvesting to reduce surface fuels during harvesting, as opposed to cut-to-length methods, which can sometimes double the amount of fuel remaining. However, the authors noted that the markets influence the harvesting method used, as is the case with debris pile utilization. The manner in which material is removed from a site depends on commercial market demand and the willingness to expend costs for utilization (Evans et al. 2011). In most cases, the cost of transporting biomass is high due to transportation distance and small piece size. This makes it challenging to support the argument for increased utilization. Mitchell and Gallagher (2007) also experienced high transportation costs in their chipping study, reporting only a 25% utilization rate based on transportation distance and time between loads. Mitchell and Smidt (2019) noted that 7 t/ha was considered the average minimum amount required to make the cost of chipping economic.

Foltz and Wagenbrenner (2010) investigated the amount of mulch debris that can be used for erosion control in post-burned sites. They noted that applying woody material to disturbed surfaces (in this case, mulch) provides immediate ground cover that can reduce runoff and retain moisture. The authors focused their work on lodgepole pine slash fuels <2.5 cm in length, as these fine fuels are not thought to contribute to erosion control; rather, they are thought to add to the overall weight of the debris and increase the cost of application. Three mixes were made that contained the following: mulched material without modification, mixed material with 50% less fine fuel (<2.5 cm in length), and reduced material, with all fines removed.

The first mix significantly reduced runoff compared to controls with no mulch (bare soil) when applied at 70% coverage. Sediment control required applying 50–70% where rainfall was the main condition being managed. The second mix, with half the fines removed, yielded the same results. The third mix, with all fines removed, performed better than the others, with runoff and sediment control witnessed at 50–70% cover. The authors attributed this result to larger material size being more stable than the finer debris. Therefore, mulched material that results in larger piece sizes could be marketed for erosion control and be a commercially viable product (Foltz and Wagenbrenner 2010).

A study in Spain investigated using mulch for erosion control but added a step by testing mulching treatment before salvage logging in a real post-wildfire scenario (Fernández and Vega 2016). Eucalypt bark mulch was spread across the burned area to achieve >80% cover and a depth of 3 cm. The authors found that mulch significantly reduced sedimentation of their site during the six months between wildfire and salvage logging operations. The amount of bare soil increased 18 months after salvage: 35% of mulched areas were bare, and 85% of non-mulched sites were bare. The authors found that where mulch was applied before salvage logging, erosion was significantly lower than at sites where no mulch was applied, and salvage logging followed. They recommended that mulch be applied to post-burned sites immediately to enhance erosion control, which may be especially important in areas where flooding events in fall and spring are expected to worsen after the wildfire season (Fernández and Vega 2016).

Uzunovic and Semple (2019) evaluated wood chip production in Canada and its potential in international markets. Many potential uses for wood chips exist across the global market, including mulch for gardens, smoking of meats, growth substrate for mushrooms, animal bedding, and fibre-based composites, as well as in larger markets such as bioenergy and pulp wood (the largest market) and many others. The use is determined by the size and cleanliness of the chip, and the presence of bark. Bark on the chips limits their marketability as it can contain invasive insects, viruses, bacteria, or fungi (Uzunovic and Semple 2019).

The Cariboo Region of BC is a primary supplier of chips for wood pellet production in Canada. Due to the need to process burnt salvage trees and those killed by bark beetles, there is an abundance of low-quality chips that are not usable in pulp mills (Uzunovic and Semple 2019). Chip exportation is highly regulated in BC to ensure that local industries have enough material before excess can be shipped to foreign markets. The exception to this regulation is shipping pulp-grade logs from western Vancouver Island to China. Chips can be shipped via rail to other provinces from Prince George and Prince Rupert. In the past, Japan and Turkey were big importers of Canadian wood chips, but currently, the major markets are the UK and Singapore. Other potential markets include (in order of volume that could be used) China, Taiwan, and Korea. Due to concerns with the pinewood nematode (*Bursaphelenchus xylophilus*), the European Union has numerous measures in place to protect them from infestation, which almost eliminates importation of Canadian wood chips even though the European Union needs them (Uzunovic and Semple 2019).

Spencer and Röser (2017) compiled a report with guidelines on extracting low-quality fibre from forests in BC. Chippers create high-quality pulp chips or low-quality fuel chips. Wood chips destined to become pulp cannot contain bark, branches, or needles. If chips are stored to be transported later, the operator packing the chips should leave the bottom 10% of the chips in the pile to decrease the possibility of the loader scooping soil along with the chips.

Jain et al. (2012) reviewed fuel management practices in northwestern US. When reviewing the economic potential of fuel treatments for a site, the authors found that "dirty chips" that are destined for energy wood generated less than half the total value of that at a given site. They suggested that if costs to haul material from the site are high, burning the chips may make more economic sense than hauling them to a bioenergy facility. However, this option requires weighing the wasting of carbon against using it as an energy source.

Volpé (2018) reviewed the best management practices for assessing quality forest feedstocks for power and heat generation. The author defined the following as the critical attributes for this purpose: moisture content, particle size, bulk density, and contamination level. Moisture levels affect boiler efficiency (higher moisture content decreases boiler efficiency), while bulk density affects transportation costs (low bulk density increases costs by being less compact). If particles are too large (>100 mm), they may clog the delivery infeed system of small-scale boilers. If the particles are too fine (<3 mm), fly ash could be increased. Ensuring the feedstock is free of soil, sand, gravel, rocks, metal, and chemicals varies in importance, depending on the type of use the biomass is destined for. Bioenergy processes typically use roundwood, wood chips (clean or dirty), sawmill bark (including hog fuel), and legacy bark piles as fuel.

Volpé (2018) described clean chips as being of pulp quality (<6% bark), supplied by local sawmills, and dirty chips as derived from chipped roundwood (9–15% bark) or tops and branches of trees (25–50% bark/foliage). The author specified the best management practices for the supply and storage of chips destined for feedstock, as well as the quality assessment process. Wood chip piles should be tarped from top to bottom, and if possible, they should be contained in a shelter. Passive ventilation should be used between the tarp and the pile to eliminate condensation. A benefit from covering the piles is reduced ice build-up on the outside of piles during winter storage and the associated increased moisture content. Chips should be stored for less than six months, and piles should have a 1:3 maximum height-to-width ratio, with a height of less than or equal to 7 m. The storage surface should be clean, paved, and well draining. Piles should not be shovelled in winter. This will ensure that snow, ice, or rocks are not thrown into the pile.

Volpé (2018) also suggested that samples should be taken at the mill gate during loading, for quality assessment. Quality assessments consider moisture content, temperature, particle size, and bulk density. Moisture content can be sampled in different ways, depending on the location of sampling (mill gate or yard). At the gate, one in five truckloads should have three 2 L samples per point of origin (cutblock of the same supplier/sawmill origin). If the sampling occurs in the yard, three 2 L samples should be taken per 1000 oven-dried tonnes (odt) per month. The sampling method involves drying the chip samples at 105°C for 24–48 hours until the weight stabilizes. Temperature sampling should be done monthly, with manual probing at 1 to 2 m depth on all sides of the pile, or 5 probes per 1000 odt per month. Particle size sampling at the mill gate should occur in one in five truckloads; three 10 L samples should be taken per point of origin. In the yard, particle sampling should occur every two months; three 10 L samples should be taken per 1000 odt. Particle size should be tested by sieving the chips in a vibrating screener. Finally, bulk density should be tested in one in five truckloads, and two 50 L samples should be taken per point of origin. In the yard, bulk density should be sampled by taking two 50 L samples per 1000 odt every two months. Bulk density is tested by loading chips into a 50 L stainless steel bin (Volpé 2018).

Stephens et al. (2012) wrote about the economic barriers of utilizing material removed from fuel treatments in timber or biomass markets. The authors noted that although using downsized equipment for smaller trees or small treatment units may seem a worthy idea, the economic costs are substantially higher than those of conventional equipment operating under good conditions. The authors also noted that using mastication equipment to collect woody biomass is a promising method to treat smaller materials in bulk, but that utilization of woody biomass will likely be determined by the proximity of the forest to a conversion facility that can process it, as truck transportation is expensive.

Sikka et al. (2013) noted ecological concerns about transitioning from fossil fuel to biomass heating in Alaska. This switch could cause more overextraction from forests for the sake of generating heat and electricity and could have potential negative impacts on soils, nutrient cycling, or ecological processes by removing all logging residues. The authors also mentioned that transporting great amounts of biomass may cause harm through increased road construction and emissions from transport. There are economic constraints, and the initial one-time investment in infrastructure is quite costly. It is likely that converting southeast Alaska to biomass heat will need government policy changes and subsidies, such as those that exist in the Netherlands, Finland, and Sweden, for biomass heating. Before switching to biomass heating, the authors recommended asking several key questions: (1) What potential do local sources of biomass have for meeting energy needs? (2) How will developing a wood-biomass energy sector affect the forest ecosystems? (3) What are the key economic thresholds for transitioning to biofuels? (4) What kind of public–private partnerships and policies are needed to promote the transition to sustainable biomass energy? and (5) What is needed to build community support for biomass energy?

Coote (2012) noted that pellets are more expensive than fuelwood (firewood) or chips and that they require pellet manufacturers and a supply chain. Wood chip combustion systems require chips that are produced in similar ways to mulch, but with tighter restrictions on chip particle size. The author warned that while chip heaters are like pellet heaters, the storage silo tends to be larger for chips, and this tends to be more expensive. Biomass heating systems range from a few thousand dollars for an efficient residential pellet heater to a hundred thousand dollars or more for a system that could supply heat to a community, campus, or large building.

Battaglia et al. (2010) found that mulching removed many trees <10 cm in diameter, as well as many overstorey trees, resulting in a lower canopy bulk density and higher live crown height in all stand types except those dominated by juniper. Mulching (which was used as an umbrella term for chipping and mastication) reduced basal area by 47–89% and density (stems per hectare) by 69–97% in each forest type studied (lodgepole pine, mixed conifer, ponderosa pine, and juniper). The greatest reductions were in lodgepole pine and mixed conifer stands, followed by ponderosa pine and juniper stands. Mulching significantly increased the diameter and canopy base height of the residual stands and significantly reduced canopy bulk density in all stands except juniper. However, the surface fuel load that resulted from mulching was proportional to the reductions in the overstorey and ladder fuel load density in all sites (Battaglia et al. 2010). The authors suggest using of more targeted mulching prescription for crown fire reduction.

Disc trenching is a technique historically used for creating an environment suitable for planting new trees after a commercial harvest or wildfire (pers. comm. C. Vandergaag and R. Hall). This practice creates a furrow or trench in the soil of the forest, and new trees are planted in the furrow, on the side or on top of the berm, depending on the local climate. Disc trenching could be used to break up fuelbed continuity and increase the amount of mineral soil that is in contact with chips in a masticated fuelbed. The increased soil contact is likely to decrease the probability of ignition and fire behaviour and can increase the rate of decomposition. However, there are limitations in terms of where this practice can be used. Further research is needed on disc trenching in masticated fuelbeds.

2. Fire Behaviour

2.a. Fire Intensity and Severity

Chipping

Hvenegaard (2013) reported that the rate of spread in a chipped ROW varied between 0.03 and 0.5 m/min. This resulted in a 5 cm maximum burn depth and minimal consumption of the chipped fuel. When evaluating probability of ignition using the match drop test, Hvenegaard (2014) found the probability of ignition to be 85% in the ROW, 46% in the surrounding buffer, and 0% in the standing timber. Hvenegaard (2013) reported fires in the ROW as burning for two minutes, with a flame length of 15 cm and a growth limited to 50 cm. Smouldering depth was predicted to reach 10 cm based on the moisture content of the fuelbed (Hvenegaard 2013). Ignition potential was estimated to be greatest when the Fine Fuel Moisture Code (FFMC) reached 82, but the fuelbed could ignite at FFMC of 80, based on two years of data (Hvenegaard 2014). Hvenegaard (2014) also determined there was no difference in ignitability between years, and that ignitability would decrease as new vegetation shaded the fuelbed.

Glitzenstein et al. (2006) found no significant differences in flame height or spread rate in chipped versus non-chipped plots during a prescribed fire in North Carolina. However, a significantly higher proportion of the area in the untreated plots burned (80%) compared to in the chipped plots (approximately 50%). The chipped plots also had moderately lower mean scorch height than untreated plots (Glitzenstein et al. 2006). Sparks et al. (2017) conducted a prescribed fire in thinned and chipped fuel reduction sites. Most of the test plots exhibited smouldering (97.3% of burn duration), while a minority of them displayed long flame length and high rate of spread (Sparks et al. 2017).

Morrow and Hvenegaard (2016) evaluated fire behaviour in chipped beds in the Northwest Transmission Line ROW. In an observed fire, the flame length was 0.3 m, and the rate of spread was 1.5 m/min; these values doubled if fire hazard conditions went from the 75th percentile to the 90th percentile and if wind speeds were doubled. Cured grass under the same conditions would spread much faster than the chipped beds of the ROW. The presence or absence of chips had little impact on the wildfire threat score, and the ROW had lower scores than the adjacent standing forests. In the ROW, areas with chips scored higher in potential fire behaviour than those without chips. Morrow and Hvenegaard (2016) recommended that hazard reduction activities be conducted where chip beds are deep (15 cm or deeper) and cover areas are at least 0.1 ha.

Morrow and Hvenegaard (2016) reported three options for hazard mitigation in the chipped beds of the Northwest Transmission Line ROW. Mitigation efforts should focus on altering the dryness and continuity of the chipped areas. The authors listed these in order of effectiveness and cost, from highest to lowest (Table 10). The document also reported specific standards for each treatment (pages 17 and 18 of

Morrow and Hvenegaard 2016). Once the standards are met in the strategy that involves trench or spot disturbance and seeding with low-flammability plant species, abatement should be considered successful. When 80% or more of all chip beds in an area are covered with green, low-flammability vegetation, abatement can be considered successful in the seeding only strategy. The authors also provided best practices for future chipping treatments (pages 20 and 21 of Morrow and Hvenegaard 2016).

Table 7. Chip wildfire hazard mitigation strategies

Wildfire hazard mitigation option	Estimated time for mitigation (years)
Trench or spot disturbance and seeding with low-flammability plant species	1–2
Seeding only – with low-flammability plant species	4–6
Monitor	6+

Table 10. Chip mitigation strategies (Table 7 from Morrow and Hvenegaard [2016]).

Mulching

Based on the increased continuity of 1-h and 10-h fuels in mulching treatments, Battaglia et al. (2010) noted a potential shift in surface fire behaviour compared to untreated sites. These shifts could include reduced rates of spread and flame length but increased smouldering and flaming duration. Although crown fire is reduced, the increase in woody fuel cover and load may lead to more intense surface fires that become difficult to control. The authors proposed that experimental burns be conducted in mulched sites to assess fire behaviour and provide more accurate modelling parameters.

Hvenegaard and Price (2018) performed a prescribed fire on mulched fuelbeds using line and point ignitions. In the line ignition trial, they recorded the average flame height as 0.5 m (with a maximum of 2 m) and the average rate of spread as 3.1 m/min (fastest speed was 4.6 m/min). In the point ignition trial, performed the following day, the average flame height and rate of spread was 1 m (max. 2.5 m) and 1.1 m/min (max. 2.2 m/min), respectively. In the point ignition trial high-intensity fire developed, with fire whirls and spotting up to 80 m ahead of the flaming front. Fire re-ignition was noted in mulched fuels even after the open flame was suppressed. Hvenegaard and Price (2018) mentioned this was a concern in drier fuelbeds, which require more extensive mop-up. Following the fire, the depth of burn was 3.4 cm and 3.9 cm for the line and point ignitions, respectively, resulting in one-third mulch consumption and leaving more than half of the fuelbed intact. The authors reported that from previous studies, certain trends could be seen, including an increased rate of spread and flame length with increasing initial spread index. These findings require more data but provide a basepoint for expected fire behaviour in mulched fuelbeds. Compared to the open-fuel types in the Fire Behaviour Prediction system, observed fire behaviour in mulch tends to exhibit lower actual rate of spread and fire intensity than predicted, and more fuel consumption compared to the O-1a and O-1b fuel types but less than S-2 fuels (Table 11) (Hvenegaard and Price 2018).

Table 5. Observed fire behaviour during May 31 trial, with predictions for other Fire Behaviour Prediction (FBP) open fuel types

Weather and Fire Weather Index values				Fire behaviour				
					Observed[a]	FBP predictions[b]		
FFMC	Average wind speed (km/h)	ISI	BUI		Mulched fuel	O-1a	O-1b	S-2
93	11.6	11.8	69	Rate of spread (m/min)	0.9 (average) 2.2 (maximum)	36	39	8.5
				Fire intensity (kW/m)	1 875[c]	3 255	3 553	29 578
				Fuel consumption (kg/m^2)	3.6	0.3	0.3	11.8

[a] Fire behaviour values are based on the observed maximum rate of spread and maximum flame height.
[b] FBP predictions for O-1a (matted grass) and O-1b (standing grass) are based on a default fuel loading (Taylor et al., 1997) of 3 tonnes/ha (0.3 kg/m^2) with a 100% curing rate.
[c] Calculated using Byram's fire intensity equation $I = 300 L^2$ where I = fire intensity and L = flame length. Maximum flame height recorded for the May 31 fire was 2.5 m. Minimal flame tilt was observed on the flame front, and flame length was considered to be equivalent to flame height.

Table 11. Chipped fuels vs. other fuel types (Table 5 from Hvenegaard and Price [2018]).

Battaglia et al. (2009) found that mulched mixed conifer and ponderosa pine stands required winds of 56 km/hr or greater to sustain active crown fire and that the crowning index after treatment was greater than 72 km/hr.

Brockway et al. (2009) used prescribed fire on mulched sites, noting that the mulch burned poorly, which they attributed to flame temperatures never going beyond 185°C. Delays between treatments also allowed hardwood seedlings and vines to re-establish in dense patches after mulching, which likely hindered the fire effects. Regardless, the authors recommended using prescribed fire on mulched sites to remove competing vegetation in longleaf pine (*Pinus palustris*) ecosystems and to maintain frequent surface fire disturbance (Brockway et al. 2009).

The rate of fire spread in black spruce and jack pine (*Pinus banksiana*)that had been mulched a year prior ranged between 0.009 m/min and 10 m/min, averaging to be 0.6% of the wind speed (Moore et al. 2020). The average depth of burn was 3.5 cm, but the authors recorded a maximum of 6.5 cm in places. Consistent with Hvenegaard and Price (2018), Moore et al. (2020) found lower fire intensity and spread than that predicted in the slash models of the Fire Behaviour Prediction system. They reported 88% less spread and 98% less intense fire behaviour than with the S-2 fuel type, which was attributed to fuelbed composition. Mulch has less dead and cured foliage and more coarse woody fragments than slash, both of which influence fire intensity (Moore et al. 2020).

Hvenegaard and Schroeder (2015) conducted a single replicate study that evaluated the impacts of strip mulching on fire behaviour. The results were mixed; strip mulching did not affect fire behaviour and rate of spread, but fire intensity was reduced. Ground fuels that intensified fire behaviour included dried mulch and feather moss. All trees in the study area candled, which created a source of embers.

Hvenegaard (2017) mulched 0.27 ha of a jack pine and black spruce stand in the Northwest Territories at the Canadian Community Boreal FireSmart project in 2011. Mulching was done in a grid pattern, and mulched strips had 4 m by 6 m dimensions. Residual trees were clumped together, and no in-clump limbing or thinning occurred. To test the effectiveness of this treatment, experimental fire was applied in 2016, five years after mulching. The experimental fire was started in untreated forest adjacent to the mulching treatment during a day with temperature (31°C) and relative humidity (30%) crossover and moderate wind speeds (14 km/hr). The fire in the untreated forest built up a head fire intensity of 10,000 kW/m and spread to the treated forest in 1 min 15 sec, with a spread rate of 12 m/min. When the fire entered the treated forest, fire intensity dropped and peaked at 6,000–8,000 kW/m. The overall rate of spread averaged at 11 m/min throughout the treatment and burn time. However, surface fire intensity was still quite high, and passive crown fire occurred. The fire in the treated forest had a crown fraction burn of 90% and a depth of burn that spanned 0–4 cm through variable surface fuels. The resulting fire behaviour would still challenge direct attack by suppression crews, though aerial suppression may be successful.

Wolk et al. (2020) compiled the existing data on mulched (masticated and chipped) fuelbeds in Colorado into a report to define the benefits and limitations of the technique, including the effects of mulching on fire behaviour. Surface fuel load at mulched sites was three to six times greater than at untreated sites, and the fuelbeds were denser, more compact, and more continuous than at the untreated sites. Increased surface fuel loading resulted in higher scorch height and root damage for trees in or near the mulched fuelbeds. While mulching can shift fire behaviour from crown fire to surface fire, which typically has a flame length less than 3 ft. (1 m) under mild burning conditions and is easier to suppress, the trade-off is that the combustion of woody debris produces more energy and burns for a longer amount of time. While mulched fuelbeds are harder to ignite than herbaceous or needle litter fuels, beds smoulder and burn for long periods of time (days to weeks) compared to other woody fuels, pine needles, or grass (minutes to hours). Woody material left behind by mulching can remain flammable for at least 10 years. The smouldering time of a mulched fuelbed was found to increase with the density of the bed. Fire intensity can be affected by the presence of easily ignitable vegetation growing in the bed. Fuelbed bulk density also changes depending on the types of trees in the stand. Masticated pinyon pine–juniper forest has double the density of ponderosa pine–oak forest or Jeffrey pine–white fir forest.

Hvenegaard (2020) compared the effects of mulching on fire behaviour at three treatment intensities: low intensity (minimal mulch debris particles, greater volume of coarse woody debris, undisturbed moss layer), normal intensity (aerial and surface fuels processed as chipped debris, some disturbance of duff layer), and high intensity (high percentage of mulched debris in size classes 1 and 2, greatest mixing of duff and mineral soil). At low wind speeds, the rate of spread was 0.16 m/min for regular mulch and 0.27 m/min for coarse mulch; fine mulch did not burn except in places where it was directly torched. The author suggested that the compact bed likely inhibited the movement of air through the mulch. With stronger wind speeds, the rate of spread was 0.2 m/min for fine mulch, 0.3 m/min for regular mulch, and 1.2 m/min for coarse mulch. The highest fire intensity and longest flame height were observed in coarse mulch, which had a fireline intensity of 400 kW/m (with peaks of up to 800 kW/m during wind gusts).

Clark (2008) compared mulchers with feller/processors to see which equipment is better for creating firelines. One advantage of mulching is that ignition potential in mulched material immediately after processing is likely lower than unmulched debris due to the moisture in the mulched material.

Mastication

Mastication involves chipping small trees or slash, resulting in a fuelbed that can be difficult to ignite. However, it may also result in increased tree mortality due to increased soil temperature in cases of ignition (Evans et al. 2011). Thompson et al. (2016) performed laboratory burns on masticated fuelbeds (which the authors called *mulch*) to better understand the carbon production and energy release associated with burning such fuels. Woody debris was collected from a masticated site of lodgepole pine and black spruce in Alberta and was sorted based on fuel size class (<0.5 cm, 0.5–1.0 cm, and >1.0–3.0 cm), but little interaction between particle size and combustion metrics was found. Moisture content had a greater influence, and Thompson et al. (2016) found that the average flaming duration was longer in wetter fuels and shorter in drier fuels, which was the opposite of smouldering duration. However, the authors noted that the flaming and smouldering witnessed in their study would occur in the field only under extended rain-free periods with significant fuelbed drying, such as during extreme droughts.

In a study by Kobziar et al. (2013), two prescribed fires were conducted in masticated fuels. The first was a laboratory-scale fire, which involved collecting masticated fuels from a site, drying them, and creating fuelbeds that were then burned using strip head fire. The field-scale fire took place in the masticated site, with no manipulation of the fuels. In both fires, Kobziar et al. (2013) noted that rate of spread was unaffected by fuel load and was more related to fuel moisture. Consumption of fuels did not differ by treatment type (plantation, recently burned mature sites, and mature pine stands) but was higher in the laboratory fires. Exposure to lethal heating increased with fuel load, but soil temperatures never exceeded 60°C, even when depth was as low as 2 cm and soil was dry (Kobziar et al. 2013). The authors noted, however, that soil temperature rose more under deeper fuel load and drier conditions, remarking that for every 10 t/ha of fuel load, the duration of time soil temperature remained >60°C increased by 5 minutes. In the field-scale fire, flame length was lower in treated versus untreated sites but was more correlated with shrub regrowth than masticated fuelbeds were (Kobziar et al. 2013).

Kreye et al. (2013) investigated fire behaviour in masticated fuelbeds dominated by litter and shrub material vs. woody debris. They were interested in the interaction between fuel load and moisture content with fire and heating in a fuelbed with a lower bulk density than typical masticated fuelbeds. They found increased flame length, fireline intensity, and periods of lethal heating with increased fuel load, but they recorded no influence of fuel load on rate of spread or consumption (Kreye et al. 2013). Additionally, higher fuel moisture content reduced flame length, intensity, and rate of spread, but did not impact consumption, surface temperature, or duration of lethal heating (Kreye et al. 2013). These results are worth considering when performing mastication in stands that may target more shrubs than small trees, or where needle and leaf litter accumulates on the forest floor, as the expected fire behaviour will differ from that on sites with more woody material produced after treatment.

Wilkinson et al. (2018) performed a prescribed fire in two different mastication treatments: one that mulch thinned the site and another strip mulched with 5 m wide swaths between 5 m natural forest. Average surface temperatures prior to the prescribed fire were higher in the treatment areas compared to control sites, likely due to increased solar radiation and evaporation resulting from canopy openings (Wilkinson et al. 2018). Treatments were dominated by feather moss, which held significantly less moisture within the upper 6 cm than the sphagnum moss found on the controls. Lower depth of burn was found where more sphagnum existed (Wilkinson et al. 2018).

Schiks and Wotton (2015a) used the two-minute match drop test in masticated fuelbeds, avoiding pieces >1 cm in diameter. If ignition occurred and burning sustained for 120 seconds, the test was considered successful and therefore conducive to firebrand spread. This test was done in the field and in the laboratory to assess for specific variables, such as moisture content, which was found to have a significant influence on fuel ignition (Schiks and Wotton 2015a).

Murphy et al. (2010) produced a table that outlines specific details about 20 fires over an 11-year period in northern California and the interactions of the fires with the fuel treatments in their project area. Where thinning and mastication occurred, the authors noted modified fire behaviour, specifically, reduced flame length and slower rate of spread. However, the fuel density increased fire intensity and residence time and ultimately led to high tree mortality. The treated sites were easily accessed and could be used as anchor points during suppression efforts for safer and more effective fire suppression (Murphy et al. 2010).

Hvenegaard et al. (2016) performed a prescribed fire that went through two different mulch treatments: strip mulching and mulch thinning. At the strip-mulched site, the rate of spread was similar to the values predicted in the Fire Behaviour Prediction system for C-2 fuel types. However, the authors observed crown fire initiation and spread within the untreated strips, which influenced the resulting fire intensity observations. They noted that with wider mulched strips (4 m swaths in the study), the residual forest patches remained at risk of crown fire and ember transmission. The results from the mulch-thinned site were difficult to isolate because of the influence of the fire in the adjacent strip-mulched site. The expected fire behaviour in untreated sites will affect the treated units and how they are designed. Based on their study, Hvenegaard et al. (2016) recommended against leaving patches of residual fuel (retention areas or strips) that could support crown fire initiation and ember creation, as spot fires may develop in untreated stands outside the treated area.

Morgan et al. (2018a) evaluated fire behaviour of ponderosa pine fuelbeds created by mastication. The fine masticated material had significantly higher flame length in the laboratory, but the rate of spread and consumption did not differ, and both fuel types resulted in long smouldering times (Morgan et al. 2018a).

In a literature review by Kreye et al. (2014), flame length in masticated fuelbeds varied from 0.12–1.70 m across ecosystems in the US. Longer flame length was associated with reduced fuel moisture (which ranged from 2.5–16%) and higher fuel load (10–169 t/ha) across the sites (Table 12). The authors noted that average flame length increased with average fuel depth, but where fuel depth was controlled, fuel moisture was the key factor influencing flame length and flaming duration. In prescribed fire situations, flame length varied between 0.26 and 1.88 m, similar to that in laboratory experiments (Table 13). However, the authors warned that findings from laboratory burns may not accurately represent operational fire behaviour due to factors such as wind or weather shifts, which are challenging to replicate. Flame length was not related to fuelbed depth in the field burns as much as in the laboratory burns because operational fuelbeds are heterogeneous and influenced by weather. Fuel consumption also varied in the laboratory burns (76–98%) compared to the field burns (47–93%) (Kreye et al. 2014).

Lyon et al. (2018) performed laboratory- and stand-level prescribed fire experiments on coarse- and fine-grained masticated fuels. In the laboratory, average flame length was greater in the fine-scale treatments than in coarse-scale treatments in the second year after treatment, but not in the first. Conversely, the rate of spread was significantly influenced by soil moisture, but in year two, the differences were negligible. Consumption of fuel in general was greater in year 1 than in year 2. However, it appeared that neither consumption nor rate of spread differed significantly between the two treatment levels (coarse and fine). Lyon et al. (2018) found different results in stand-level prescribed fire treatments, in that no significant differences in fire behaviour were observed between masticated and control plots. This contradicts other studies; however, the authors suggested it may be a result of the relatively moist conditions that the experiments were performed under. This suggests that mastication is more likely to influence fire behaviour in drier conditions and with higher fuel loading. In general, fuel consumption was higher in plots with fine mastication, and deeper fuelbeds had a higher rate of spread and greater flame length. Masticated fuels were generally mostly combusted via smouldering, which may increase fine particulate emissions compared to combustion via flaming (Lyon et al. 2018).

Table 2
Fuel bed characteristics and fire behavior results from laboratory fires in masticated fuels. Fuel bed loadings were calculated based on the burn platform size and mass of masticated fuels on the platform, then scaled up to corresponding Mg ha^{-1}. Variables explicitly tested within studies are in bold. The parent material (i.e. overstory or understory) of the bulk masticated particles used in the experiments are indicated by *.

Overstory vegetation (State)	Dominant understory species	Fuel bed loading (Mg ha^{-1})	Depth (cm)	Bulk density (kg m^{-3})	Fuel moisture (%)	Flame length (m)	Flame residence time (min)	Consumption (Mg ha^{-1})	Consumption (%)
*Mixed Conifer (ID)[a]	*S. albus, V. cespitosum*	56.7	5.5	105.5	**3–8**	0.30	7	52.1	90.3
*Mixed Conifer (ID)[a]	*S. albus, V. cespitosum*	57.6	5.9	96.5	**10–12**	0.23	10	51.7	91.3
*Mixed Conifer (ID)[a]	*S. albus, V. cespitosum*	59.3	5.8	104.3	**13–16**	0.12	14.8	54.1	89.7
18 yr old Ponderosa Pine[b]	**A. viscida, A. manzanita*	**34.0**	**2.5**	133.0	16	0.3–0.4	20.0–26.0	26.0–27.0	76.0–79.0
18 yr old Ponderosa Pine[b]	**A. viscida, A. manzanita*	**101.0**	**7.5**	133.0	16	1.0–1.1	23.0–26.0	90.0–93.0	89.0–91.0
18 yr old Ponderosa Pine[b]	**A. viscida, A. manzanita*	**169.0**	**12.5**	133.0	16	1.3–1.7	27.0–28.0	154.0–159.0	91.0–94.0
Mixed Conifer (CA)[c]	***Fractured A. manzanita***	73.8	7.0	105.4	**5**	0.70	17.4	69.6	94.3
Mixed Conifer (CA)[c]	***Intact A. manzanita***	73.8	7.0	105.4	**5**	0.91	13.8	71.7	97.2
Mixed Conifer (CA)[c]	***Fractured A. manzanita***	73.8	7.0	105.4	**13**	0.53	23.3	70.5	95.5
Mixed Conifer (CA)[c]	***Intact A. manzanita***	73.8	7.0	105.4	**13**	0.75	18.8	72.8	98.6
Mixed Conifer (CA)[c]	***Fractured C. velutinus***	73.8	7.0	105.4	**5**	0.63	16.2	69.7	94.5
Mixed Conifer (CA)[c]	***Intact C. velutinus***	73.8	7.0	105.4	**5**	0.65	18.1	70.9	96.1
Mixed Conifer (CA)[c]	***Intact C. velutinus***	73.8	7.0	105.4	**13**	0.58	22.6	68.0	92.2
Mixed Conifer (CA)[c]	***Fractured C. velutinus***	73.8	7.0	105.4	**13**	0.61	21.5	70.8	95.9
Mixed Conifer (CA)[c]	**A. manzanita*	73.8	7.0	105.4	**2.5**	0.95	13.2	69.5	94.2
Mixed Conifer (CA)[c]	**A. manzanita*	73.8	7.0	105.4	**7**	0.79	17.3	69.5	94.2
Mixed Conifer (CA)[c]	**A. manzanita*	73.8	7.0	105.4	**9**	0.77	17.4	69.9	94.7
Mixed Conifer (CA)[c]	**A. manzanita*	73.8	7.0	105.4	**11**	0.69	22.3	68.9	93.3
Longleaf Pine (FL)[d]	**S. repens, I. glabra*	10.0	6.0	16.7	**9**	0.69	na	9.1	90.7
Longleaf Pine (FL)[d]	**S. repens, I. glabra*	20.0	9.0	22.2	**9**	1.06	na	18.4	92.0
Longleaf Pine (FL)[d]	**S. repens, I. glabra*	30.0	12.0	25.0	**9**	1.59	na	29.4	98.0
Longleaf Pine (FL)[d]	**S. repens, I. glabra*	10.0	6.0	16.7	**13**	0.29	na	9.8	97.7
Longleaf Pine (FL)[d]	**S. repens, I. glabra*	20.0	9.0	22.2	**13**	0.76	na	19.3	96.3
Longleaf Pine (FL)[d]	**S. repens, I. glabra*	30.0	12.0	25.0	**13**	1.14	na	29.1	97.0

[a] Brewer et al. (2013) used a 0.37 m^2 platform.
[b] Busse et al. (2005) used a 0.9 m^2 platform.
[c] Kreye et al. (2011) used a 0.26 m × 0.38 m platform.
[d] Kreye et al. (2013a) used a 4.0 m diameter circular platform.

Table 12. Fuelbed characteristics and fire behaviour (Table 2 from Kreye et al. [2014]).

Table 3
Field observations of weather, fuel bed characteristics, fire behavior variables, and post-fire consumption in masticated fuels. Bold variables were tested within a particular study.

Dominant masticated material	Weather conditions			Fuel characteristics			Fire characteristics			Post-fire	
	Temperature (°C) month	Windspeed (km h^{-1})	Relative humidity (%)	Loading (Mg ha^{-1})	Depth (cm)	Fuel moisture (%)	Fire type	Rate of spread (m min^{-1})	Flame length (m)	Consumption (Mg ha^{-1})	Consumption (%)
Mixed Shrub Woodland, CA[a]	15–22 Apr/May	3.0	34–73	na	na	na	Backing	na	0.74–1.88	na	na
Loblolly Pine Coastal Flatwoods, SC[b]	NA February	12.6–23.4	na	200.4[g]	5.0–15.0	12.66–33.15	Strip Head	0.52	0.28–0.44	na	na
40 yr old Ponderosa Pine (CA)[c]	22 May/June	<5.0	33–58	60.3[h,i]	12.9	10.6–14.5	**Heading**	0.72–1.04	0.55–0.82	37.5	62.2
40 yr old Ponderosa Pine (CA)[c]	23 May/June	<5.1	33–59	60.3[h,i]	12.9	10.6–14.5	**Backing**	0.06–0.09	0.28–0.50	37.5	62.2
40 yr old Ponderosa Pine (CA)[c]	22–27 June	<5.0	32–48	26.0[h,i]	5.4	6.0–17.6	**Heading**	0.44–0.68	0.55–0.86	16.4	63.1
40 yr old Ponderosa Pine (CA)[c]	22–27 June	<5.1	32–49	26.0[h,i]	5.4	6.0–17.6	**Backing**	0.07–0.08	0.26–0.36	16.4	63.1
Ponderosa/Jeffrey Pine Plantation (CA)[d]	18.0 June	8	55	68.0[g]	na	10.0	Strip Head	0.8	0.7	32.3	47.5
Ponderosa/Jeffrey Pine Plantation (CA)[d]	19.0 June	8	54	68.0[g]	na	5.3	Strip Head	3.7	1.1	32.3	47.5
25 yr old Ponderosa Pine (CA)[e]	5–15 December	5–13	30–100	25.9[j]	2.1	4–12	Strip and Spot Ignition	na	0.97–1.06	20.6	79.5
25 yr old Ponderosa Pine (CA)[e]	5–15 December	5–13	30–100	35.0[j]	2.8	4–12	Strip and Spot Ignition	na	0.97–1.07	32.4	92.6
Longleaf Pine Flatwoods-10 + yr rough (FL)[f]	**23–24 February**	1.6–2.7	47–49	17.7[k]	6.0	12.1	Strip Head	3.4	1.1	12.6	71
Longleaf Pine Flatwoods-10 + yr rough (FL)[f]	**31–34 July**	1.6–7.2	61–76	24.1[k]	4.9	14.7	Strip Head	5.9	1.5	11.6	48

[a] Bradley et al. (2006).
[b] Glitzenstein et al. (2006).
[c] Knapp et al. (2011).
[d] Kobziar et al. (2009).
[e] Reiner et al. (2009).
[f] Kreye (2012).
[g] All woody surface fuels and litter.
[h] All woody surface fuels, litter, and duff.
[i] Kane et al. (2009).
[j] "Masticated" fuels only (differentiated from "natural" fuels, but is not clearly defined in the article).
[k] 1, 10, and 100-h woody surface fuels and litter.

Table 13. Field observations (Table 3 from Kreye et al. [2014]).

Kreye and Kobziar (2015) conducted a prescribed burn experiment on a masticated site and an untreated site in Florida, US, six months after mastication. They found that the masticated site had significantly lower flame height (33% of that in the untreated site) and lower charred bole circumference (89% in masticated vs. 99% in untreated). The rate of spread, surface litter consumption, duff consumption, crown volume scorched, maximum char height, and tree mortality did not differ significantly between the masticated and control sites. The main correlation with fire behaviour in both sites was shrub height, leading the authors to suggest that in areas where shrubs recover quickly after mastication, prescribed burning should be carried out within six months to be effective. Note that the sites consisted of longleaf pine and slash pine (*Pinus elliottii*) *overstorey* that was approximately 80 years old, last burned 10 years previously, and had no midstorey. The sites had been dominated by a palmetto (*Serenoa repens*) and gallberry (*Ilex glabra*) shrub understorey before the experiment.

In Gray (2011), masticating trees with DBH <20 cm in a mixed-species stand in Cranbrook, BC, resulted in lower canopy bulk density and higher canopy base height, creating decreases in severity of predicted fire behaviour. Gray (2011) used crown fraction burned, torching index, and crowning index to predict the treatment effect on potential fire behaviour. Crown fraction burned predictions decreased from a pre-treatment mean of 71% to a post-treatment mean of 23%. The torching index, or the minimum wind speed required to induce passive crown fire, dropped from a pre-treatment mean of 1.5 km/hr to a post-treatment mean of 24.8 km/hr. The crowning index, or the minimum wind speed required to induce active crown fire, dropped from a pre-treatment mean of 33.4 km/hr to 61.1 km/hr.

Little et al. (2019) compared the behaviour of wildfire at multiple sites in Alaska consisting of thinned sites, cleared sites, and one masticated site. Observations from a wildfire in Alaska that approached the masticated site suggested that fire shifted from a crown fire to a surface fire as it moved into the treated area, allowing responders to protect nearby neighbourhoods. However, the authors suggested that thinning (shaded breaks) might be more effective at decreasing the severity of wildfires in white spruce (*Picea glauca*)–mixed hardwood areas because masticated areas had a greater rate of spread, possibly due to drier surface fuels, the regrowth of grass and shrubs, and greater wind speed at the surface as a result of the removed canopy.

Harrod et al. (2009) reported on an earlier study in which a vertical shaft mastication head was used with an excavator to masticate and thin a forest. The fire behaviour model FMAPlus was used to predict fire behaviour before mastication, after mastication, and after mastication and a prescribed fire. The authors found that rate of spread, flame length, fireline intensity, and scorch height all decreased after mastication, and again after mastication and a prescribed fire. The authors predicted that pre-treatment stand conditions were susceptible to passive crown fire, while post-treatment conditions would burn as surface fire. These results are likely due to increased crown base height after mastication treatment.

Perrine (2015) reported on fuel treatment alteration of fire behaviour during the 2015 Card Street fire in Alaska. This wildfire burned into the Kenai National Wildlife Refuge and was attributed to human ignition. The mastication fuel treatment was 672 acres (272 ha; approximately 7.5% of the total area burned) and was completed in 1984 using tree-crushing machines. Using the Interagency Fuel Treatment Decision Support System, which uses FlamMap to model fire behaviour parameters, the pre- and post-fuel treatment fire behaviour was estimated for each treatment. Due to the age of the 1984 treatment, fuel data on the pre-treatment condition was not available. However, the untreated forest adjacent to the treatment boundaries was estimated to experience intense fire behaviour under the weather conditions occurring during the Card Street fire. Post-treatment fuels were estimated based on LANDFIRE imagery from 16 years after treatment. When modelled with the fire weather, flame length was predicted to be 1–3 ft. (0.3–0.9 m), rate of spread was predicted to be 2.3–6.6 ft./min (0.7–2.0 m/min), and fire intensity was predicted to be 13–30 Btu/ft./sec. It is likely that the surge of deciduous growth that occurred 16 years after treatment contributed to decreased fire behaviour in the treatment unit. Real-world observations on fire behaviour matched this prediction. In the mastication fuel treatment boundaries, group tree-torching occurred, but stand-replacing canopy fire did not. It also appears that fire behaviour was less intense in the fuel treatment than in the untreated areas surrounding the treatment. It is notable that this treatment likely could not have stopped the fire on its own; rather, it reduced fire behaviour enough for suppression resources to respond safely. Masticating forests allowed for pioneer deciduous species to infill the treatment unit, mimicking the historical forest mosaic while reducing wildfire severity and intensity.

Jain et al. (2012) reviewed fuel management practices in northwestern US. Mastication may increase fuel hazard in the short term (by increasing fine surface fuel loadings) but may decrease fuel hazard in the long term (by removing ladder and surface fuels). Masticated fuelbeds burn with a shorter flame length and slower rate of spread than natural or slash fuelbeds and have a longer duration of heating.

Stephens et al. (2012) do not advocate for leaving woody biomass on site after a fuel treatment if the objective is to decrease fire hazard. Instead, the authors say that whole-tree removal systems are one of the most effective systems for their ability to reduce potential fire severity and may be preferred where wood chip or biomass markets are available. They recommend subsidizing treatments or hauling costs when trees are too small for sawn products and cannot be economically chipped and transported to a processing facility.

The California Department of Forestry and Fire Protection wrote a Fuels Reduction Guide (CAL FIRE n.d.). A forest fire in Yreka, California, reached a masticated firebreak, and the rate of spread slowed as the fire transitioned from a crown fire to a surface fire, which gave firefighters time to create another bulldozed firebreak and control the fire.

Pile Burning

Murphy et al. (2010) reported on several fires that occurred in their project area and interacted with sites that had been fuel treated and pile burned. Many of these treatments were not specific to pile burning and followed mechanical or hand thinning and/or prescribed fire (Murphy et al. 2010), so it is difficult to attribute specific fire behaviour to pile burning alone. However, the following results appeared consistent where pile burning occurred:

- Open spaces are more easily defended.
- Fire intensity is reduced.
- Fire size and suppression costs are both reduced.

Although Brochez and Leverkus (2022) did not directly measure pre-treatment fuel loads in their study, they noted how the debris piles that resulted from a mechanical raking fuel treatment would be difficult to burn owing to the amount of mineral soil in the piles. Increases mineral soil was a result of the raking treatment and the goal of reaching a specific fuel load target that meant operators had to rake down to mineral soil. The authors recommended sifting through debris piles to remove soil accumulation where raking treatments occur, and to place the piles more strategically for burning. For example, many piles noted in the study were located throughout blocks and near regeneration patches and were of such a size that winter burning was more difficult as the piles were under snow (Brochez and Leverkus 2022).

Prescribed Fire

Hoffman et al. (2018) found that when fire behaviour was measured directly it was most reduced in the treatment areas that combined mechanical methods with prescribed or managed fire, resulting in a greater reduction in fire severity than in other treated or untreated areas. Prescribed fire alone has shown the potential to reduce crown fire initiation, but it is not as effective in reducing crown fire spread if canopy fuel load is not mechanically reduced (Hoffman et al. 2018).

Baxter (2013) found that under-burning of jack pine stands reduced fire behaviour eight years after treatment. The author defined under-burning as a low intensity burn that consumed surface fuels but did not impact living trees. The under-burned areas were pre-treated by removing dead material and flaky bark from trees up to 2 m in height. The results of study were based on a single replicate.

Prescribed fires in forests with heavy fuel accumulation burn more intensely than areas that experience more frequent fire returns (Marshall et al. 2008). If fire is to be used as a fuel treatment in areas it has long been excluded from, mortality of understorey species and young saplings will likely occur (Marshall et al. 2008). Continued treatments using fire will begin to alter the plant communities but these alterations will depend on the season and return interval of the prescribed fires (Marshall et al. 2008). Where prescribed fire is used every one to two years, the herbaceous layer will begin to become re-established, promoting fast-growing grasses and forbs. Longer return intervals tend to result in the growth of more woody plants (Marshall et al. 2008). The authors described the relationship between fire and woody plants as a war of attrition, in which the length of time to eliminate woody plants depends on their root reserves and on fire frequency (Marshall et al. 2008). These findings are specific to loblolly pine ecosystems; however, if specific species management is the target of a prescribed fire, these considerations remain relevant.

Agee and Skinner (2005) indicated that ground and ladder fuels may be reduced by prescribed fire but provide no specifics of fire behaviour. The authors advised that prescribed fire treatments reduce ground fuels only for a short period (<10 years), but this still allows for base height to increase before fuel load returns. The authors reported that there was no difference under the 80th percentile weather conditions for predicted flame length or torching potential between any of the treatments (prescribed fire, thinning, thinning, and prescribed fire). There were also no differences in basal area survival at either the 80th or 97th percentiles.

Brose and Wade (2002) modelled flame length in thinned and prescribed fire treatments, both under drought conditions, and found the flame length produced a U-shaped distribution. Flame length was longest (5–7 m) in simulated untreated areas. Predictions showed that flame length and rate of spread estimations dropped one year after treatment and then increased each consecutive year. These findings directly relate to wildfire control: the easiest control is during year 1 after either treatment with increasing difficulty of control each year thereafter (Brose and Wade 2002).

Carey and Schumann (2003) summarized the findings of numerous papers that investigated the effectiveness of prescribed fire in altering wildfire behaviour. Several papers showed that prescribed fire reduced future wildfire damage, including crown scorch and tree kill, as well as the size of future wildfires. Numerous other papers used models and demonstrated how prescribed fire could impact elements of fire behaviour, including flame length, rate of spread, fireline intensity, and amount of heat generated. The authors also listed empirical studies that indicate that prescribed fire influences the elements of fire behaviour, including fire severity, crown scorch, and tree mortality (Carey and Schumann 2003).

Fernandes and Botelho (2003) suggested there are many ways to assess the impact that prescribed fire has on hazard reduction. It is challenging to assess the operational effectiveness of prescribed fire, and most studies that do occur shortly after the treatment (four years or less). It can be difficult to determine the driver of the protective benefits; however, positive changes have resulted from long-term prescribed fire programs (Fernandes and Botelho 2003).

Kalies and Kent (2016) reviewed 56 studies that focused on wildfires along the west coast of the US in which treatments in the burned areas included thinning, prescribed burning, or thinning and burning. In many studies, thinning and burning was more effective than either thinning or burning alone; the combined treatment reduced fire severity, crown and bole scorch, and tree mortality. The mean effect of the fuel treatments decreased canopy volume scorch from 100% to 40% within 10 years of the treatment. Treatments seemed to be effective for 5–19 years; after that, there was no reduction of crown damage during a wildfire. The positive effects of treatment increased with the size of the treatment (>4 km^2) and decreased near the edges of the treated area. The combined thinning and burning treatment was found to be more effective in conifer forests and less effective in woodlands (interpreted as deciduous forest for the purpose of this review).

In California's Sierra Nevada, mastication generally increased surface fuel loading, although the deleterious effects on potential fire behaviour were not consistent (Hamma 2011). Forest stands treated with mastication and prescribed fire transitioned from crown fire to surface fire 10 years earlier than stands that were treated with mastication only or those that received no fuel treatment. Combined mastication and prescribed fire most effectively reduced fire behaviour via surface fuel consumption, drastically reducing flame length (Allen et al. 2023). Other studies have shown that the predicted flame length is higher for mastication only treatments than for combined mastication and prescribed fire treatments. Predictive modelling suggests that this combination effectively achieves desired fire behaviour under extreme weather conditions. In the Sierra Nevada, there may be a reason to combine mastication with prescribed fire in forests affected by bark beetle to optimize reduction of litter and duff (Birch et al. 2023). The combinations in other studies have similarly shown that combined mastication and prescribed fire reduces surface and canopy fuel load, reduces rate of spread and flame length, and makes torching and crowning less probable (Vaillant et al. n.d.). Modelling of such treatments in the Sierra Nevada suggests that the treatments may reduce landscape-level fire behaviour for up to nearly 30 years after treatment (Collins et al. 2011). Woody fuel load can vary across masticated sites; however, generally >50% of the woody fuel load is attributed to 10-h fuels (Kane 2007). A similar result was reported for creating predominantly 10-h fuels between 40% and 50% of total fuel load (Shakespear 2014). For a Sierra Nevada pine plantation, Kobziar et al. (2009) suggested that mastication alone (i.e., without follow-up treatment with a prescribed fire) may be detrimental in terms of fire behaviour during moderate to extreme weather conditions. Walker et al. (2015) examined individual tree growth in combined mastication and prescribed fire treatments. The authors found that after 10 years, the site exhibited large height and DBH increases irrespective of treatment due to the thinning protocol. However, they found overall diminished board feet and cubic volume in a thinned and burned subunit, likely due to steep reduction in volume of white fir (*Abies concolor* var. *lowiana*), while Jeffrey pine responded favourably to thinning but not to fire, and sugar pine was unaffected by either treatment.

Raking

A literature review by Evans et al. (2011) highlighted several studies that noted few benefits of raking fuels away from trees during low- and high-intensity fires. Nesmith et al. (2010) tested the effects of raking forest fuels away from individual trees to better protect them from a prescribed fire. Areas around trees were raked down to mineral soil in a 0.5 m radius from the tree base. Three years after the prescribed fire, 33% of the sugar pine were dead, with results showing a decrease in mortality with increasing stem diameter and increasing mortality with greater forest fuel depth (Nesmith et al. 2010). Raking significantly reduced tree mortality when the average forest fuel depth was high and was most effective under moderate fire intensity.

Herbicide

Brose and Wade (2002) included an herbicide treatment in their modelling study. When flame length was modelled, it resembled an inverse J as time since treatment increased (Figure 6). The predicted flame length under drought conditions was 5.2 m directly after treatment. It began declining by year 1, dropped to 2.4 m in year 2, and dropped further to 0.4 m in year 3, before increasing slightly to 1.0 m in the fifth year after treatment. The rate of spread in drought conditions mirrored flame length prediction. The initial value was 15 m/min, increasing to 18 m/min in year 1 (Figure 7), then dropping to 3.3 m/min in year 2 and 0.7 m/min in year 3, before increasing to 1.7 m/min in year 5. Ease of wildfire control based on these results would decline with time, with the easiest control occurring after year 2. The authors indicated that models showed that combined thinning and herbicide and herbicide only treatments would have similar ease of fire control at year 5 (Brose and Wade 2002).

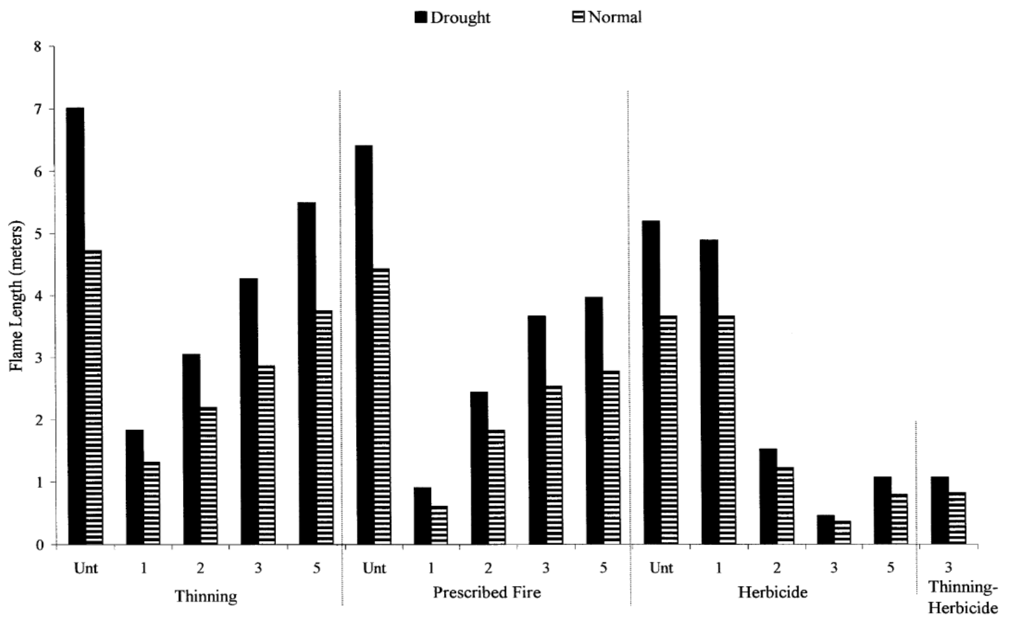


Fig. 2. Wildfire flame length predictions in untreated pine flatwood stands and in stands influenced by fuel reduction technique (herbicide prescribed fire, thinning, or thinning-herbicide), time in years (1, 2, 3 and 5) since last application of the practice and weather conditions.

Figure 6. Flame length prediction (Figure 2 from Brose and Wade [2002]).

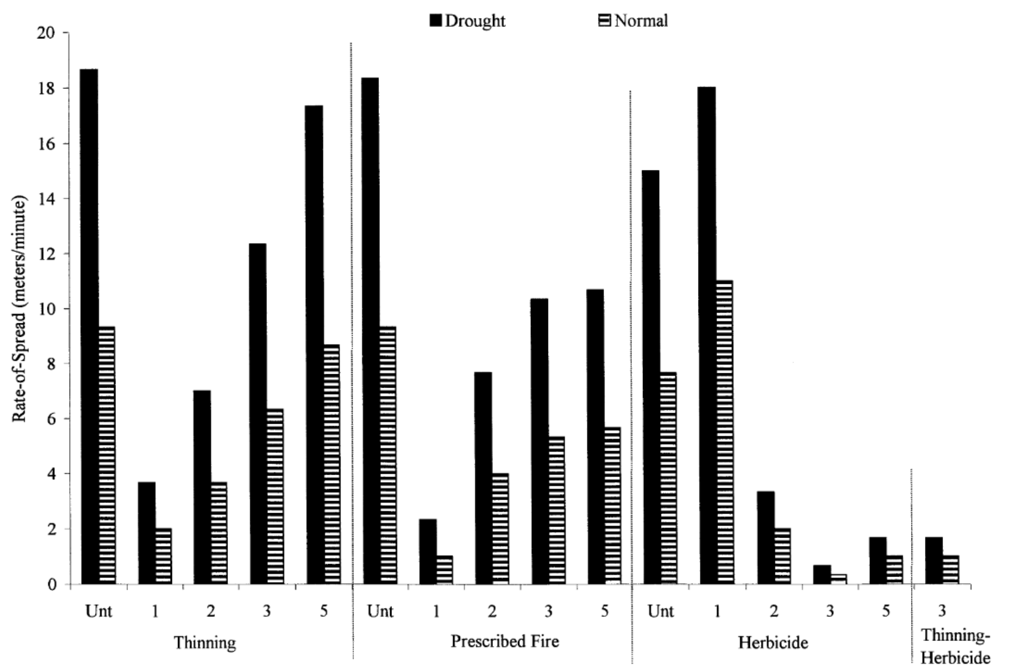


Fig. 3. Wildfire rate of spread predictions in untreated pine flatwood stands and in stands influenced by fuel reduction technique (herbicide, prescribed fire, thinning, or thinning-herbicide), time in years (1, 2, 3, and 5) since last application of the practice, and weather conditions.

Figure 7. Rate of spread prediction (Figure 3 from Brose and Wade [2002]).

2.b. Changes in Fire Behaviour Through Time

Mulching

Six months after a gridded mulching treatment in the Northwest Territories in 2011, an ignition test found that mulched debris exhibited easy ignition and sustained burning with vigorous fire behaviour (Hvenegaard 2017). However, further ignition tests under similar weather conditions in the five years after the initial tests revealed that the mulched debris became less receptive to ignition and exhibited less vigorous sustained burning. In late June 2016, the author set an experimental fire in adjacent untreated forest and demonstrated 10,000 kW/hr intensity and 12 m/min rate of spread. When the fire entered the mulch-treated forest, fire behaviour decreased but still exhibited high surface fire intensity, which led to passive crown fire in the residual tree clumps.

Mastication

A year after a prescribed fire on masticated and un-masticated sites Kobziar et al. (2013) found that only two small-diameter pines had died of the 116 that had been measured and these occurred in the burn only (unmasitcated) sites. Additionally, for the first six months after the treatments, relative humidity was lower in the masticated sites than in the untreated areas, but air temperature did not differ. After the prescribed fire, relative humidity did not differ, but air temperature was lower in the treated site from April to August of that year (Kobziar et al. 2013). No differences in relative humidity and air temperature were recorded 13–17 months after mastication and 7–11 months after the prescribed fire. The bulk density of litter and duff increased in the year after mastication, which the authors noted as being a critical consideration for subsequent prescribed fires. The moisture dynamics and vegetation recovery in masticated fuelbeds influence how a fire burns, so the authors recommended managers think through their initial treatment (mechanical) options and any additional treatments, such as prescribed fire. The authors warned that increased bulk density of fuels in the years after treatments may make consumption by fire more difficult. To minimize shrub recovery and successfully burn masticated fuels in a secondary treatment, Kobziar et al. (2013) recommended that burning be done sooner rather than later to take advantage of the fire effects.

Kreye et al. (2012) proposed that the fracturing of masticated fuels alters the drying properties of the debris. Different-sized material will react to diurnal and seasonal weather changes, which will then change the rate at which fuel moisture shifts. However, compaction could counter these effects, resulting in drier surface fuels and more moisture in the material buried beneath. To test this, the authors performed laboratory moisture experiments on masticated fuels. They found that moisture loss from entire fuelbeds composed of 1-h and 10-h fuels was slower than 10-h fuels at the surface of fuelbeds. They found no difference in moisture between fractured (masticated) and intact (whole piece) fuelbeds and individual pieces. They concluded that fuelbed properties, such as packing ratio, depth, and distribution of fuels by size class, dictated moisture loss more than piece shape did. Compact fuelbeds lost moisture at a slower rate, making them behave similarly to dense litter beds. The authors suggested that compacting masticated fuels may offset drying from solar radiation and increased wind in the newly opened stands. They caution against using fuel moisture indicator sticks as they can overestimate the probability of ignition and fire spread. This could have implications on prescribed fire success and may result in inadequate fuel consumption (Kreye et al. 2012).

Heinsch et al. (2018) found no relationship between fire behaviour and time since mastication (within 10 years after treatment). They attributed this to a lack of noticeable decomposition but noted that sites older than 10 years had more rotten wood, which would likely burn differently. In an earlier study using data from the same sites as Heinsch et al. (2018), Sikkink et al. (2017) found that time since treatment did not have a significant influence on fire behaviour except on minimum flame height. However, these authors were more interested in analyzing the chemical characteristics of masticated fuels over time, noting that particle type had more of an influence than years since treatment. Intact pieces of woody material contained more nitrogen and carbon and had higher heat values than fragmented (broken) pieces, regardless of age. Lignin was also significantly higher in intact pieces than in fragments on xeric sites, with the opposite witnessed (but results were not significant) on mesic sites (Sikkink et al. 2017). The authors concluded by saying that the following factors all influence fire behaviour: changing chemical composition with time, soil substrate underlying masticated fuelbeds, moisture in subsurface soil, and fuel load.

Keane et al. (2020) studied the drying rate of masticated fuelbeds of differing ages, ranging from 1 to 10 years since the treatment was completed. The sampled masticated fuelbeds were processed using four different techniques, which included mastication using (1) a rotating head with fixed teeth, boom mounted on a vertical shaft (five sites), (2) a vertical shaft with swinging knives, front end mounted (two sites), (3) a horizontal shaft cutting head with fixed teeth, boom and front-end mounted (five sites), and (4) chipping (one site). The samples collected from each fuelbed were saturated with water, to simulate rain, and then dried. All samples dried completely within 100 hours and were dry enough to burn after two days of drying. These results were found in the laboratory and an identical set up outdoors. There was no significant difference in drying time based on the length of time since the treatment. Three of the mastication methods had very similar drying times; the method that used a horizontal cutting shaft produced materials that dried more slowly, likely due to the larger size of particles after treatment.

In Australian shrub-dominated systems, the most recently masticated plots (0-2 years post treatment) had a threefold increase in dead fine fuels and an 11-fold increase in dead coarse fuels on the forest floor when compared to older masticated plots (3-4 years post treatment). Such increases were still evident three to four years after treatment, and flame height was projected to be lower, but no changes were predicted in rate of spread (Grant et al. 2021). In a western Mediterranean pine (*Pinus pinaster*) forest in Spain, mastication and other thinning treatments had effects that lasted at least five years after treatment in terms of reduced canopy bulk density, canopy fuel load, and under-canopy fuel load. Consequently, all of the above effects reduced crown fire susceptibility for at least five years (Jiménez et al. 2016).

Prescribed Fire

Modelling of mastication combined with prescribed fire at 10, 20, and 30% of landscape area treated suggests that combined mastication and prescribed fire at 20% of the landscape reduced fire size the most (Dicus and Osborne 2014).

In chapparal shrublands in California, mastication was effective only in the short term because the shrubs recovered quickly, and prescribed fire was compromised by the substantial and rapid increase of herbaceous fuels (Brennan and Keeley 2015). At a site in California dominated by ponderosa pine and shrubs, a study at four mulch depths (0, 2.5, 7.5, and 12.5 cm) and two soil moisture content categories (moist – simulating spring prescribed burning, and dry – simulating late-season wildfire) revealed that the potential for lethal soil heating exists after mastication, particularly in dry soil and mulch depth >7.5 cm, moist soils mitigated this lethal soil heating impact (Busse et al. 2005). A similar mitigating effect of moisture exists on soil, soil organisms, and tree roots (LeQuire 2009). At the same sites, it was shown that mastication may moderate fire behaviour but that high fuel loading can still result in substantial mortality of residual trees. The study revealed that even under the higher soil moisture conditions, a major likely cause of mortality is crown scorch, which could be mitigated by adjusting ignition techniques and/or burning during cooler temperatures (Knapp et al. 2006), and that treating masticated fuels with prescribed fire may potentially increase the resilience of stands to wildfire (Knapp et al. 2011). A study of treatments (hand thinned, masticated, masticated + prescribed fire, and prescribed fire) and an extreme wildfire in a California chaparral shrubland reported that the burn severity of vegetation and substrate was moderate across the study site and did not differ among treatments. The study also found that greater pre-wildfire fuel loading in the masticated treatments did not persist after the wildfire, and that exotic species cover in the combined mastication and prescribed fire treatment remained after the wildfire (Jones et al. 2023).

In similar California shrublands, the intensity and flaming time of masticated shrubs led to longer heating duration, and even with reduced fire behaviour, could lead to undesired fire effects (Kreye 2008). Fuelbed bulk density is likely a primary driver of fire behaviour in masticated fuelbeds (Kreye et al. 2011). The effect of age and decomposition may reduce fire intensity over time, whereby masticated fuels >10 years old burned with shorter flame height and lower fireline intensity across the fuel load. This is due to particle degradation; however, in dry environments, where degradation is slow, the risk of mortality and smoke production may persist due to protracted smouldering (Kreye et al. 2016). A modelling study across California with a 70-year treatment horizon suggested that there is great variation in treatment outcomes relative to the landscape features and size of treatment, but that reduced flame length and reduced burn severity are impacts that are seen consistently in areas affected by wildfires (Senechal 2023). In shrublands of Oregon, plots that were masticated and then burned were also reseeded with bunchgrasses. This treatment had poor success, indicating that treated plots should be monitored in the long term after reseeding (Busby and Southworth 2014).

Research in forests in Washington showed that combined mastication and prescribed fire reduced total fuel load, fuelbed depth, litter depth, and duff depth; that soil heating was relatively low in all mastication plots that were burned; and that the combination of treatments generally supported forest management goals (Clark 2009). Additional research demonstrated that mastication substantially increased the amount of coarse woody debris on the forest floor with 1-h fuels increasing, while 1000-h fuels decreased. When combined with burning, 1-h and 10-h fuels were decreased with burns being patchy in all mastication units, with low fire intensity and flame length (Harrod et al. 2008).

Research in lodgepole pine and ponderosa pine forests in Montana suggested that numerous thinning activities produce benefits, however, different thinning applications may function differently in lodgepole pine and ponderosa pine forests. The differences for mastication between forest types are unclear, except for surface fuel loading, which was lower in ponderosa pine stands (Reinhardt et al. 2010). Research in Oregon reported that thinning followed by burning treatments enhanced ponderosa pine dominance and that combined mastication and prescribed fire resulted in a fivefold increase in woodpecker nest occurrence (Sherman and Anderson 2023).

In pinyon pine–juniper woodlands of Colorado, mastication decreased tree cover and canopy fuel but increased woody and herbaceous fuels and the expansion of non-native plants, including cheatgrass (*Bromus tectorum*) and non-native thistles (no treatment combination with prescribed fire was mentioned) (Anstedt 2011, Coop et al. 2017). Similar challenges have been shown in Oregon that have implications on the season of fire (Coulter et al. 2010). Research in 45 treated sites of pinyon pine–juniper woodlands in Utah showed that mastication altered vertical woodland vegetation to predominantly 10-h fuels and that combined mastication and prescribed fire reduced the woody fuels on the surface to pre-treatment conditions. The study recommended that post-mastication burns be conducted outside the growing season in cool-weather, high-moisture conditions to remove surface fuels, mitigate lethal soil heating, and reduce plant mortality (Shakespear 2014). In Utah, managers have suggested using a treatment return interval of 10–15 years and masticating chips to the smallest size possible (Wozniak et al. 2020). Research in these plant communities in Utah also assessed the impact on soil erosion risk and found that prescribed fire (either pile burning or broadcast burning) increased wind- and water-driven erosion, but that mastication did not increase wind erosion compared to untreated sites (Karban et al. 2022).

Across 25 masticated sites in western US, Reed et al. (2020) concluded that mastication treatments that generate greater proportions of smaller-diameter fuels may result in a faster decomposition rate and mitigate fire hazards more effectively. In a pine plantation in northern California, Reiner et al. (2009, 2012) provided another refinement to the recommendation that masticated fuels should be pulled away from residual trees. The authors noted that the risk of crown fire can be further reduced if mastication is followed by prescribed fire to consume the surface fuels, but that some tree mortality is inevitable and reduction may only be marginal with pulling fuels away from tree boles while only increasing treatment costs (Reiner et al. 2009, 2012).

Across western US Rocky Mountain sites treated with mastication, there was little change to the physical and chemical characteristics of a masticated fuelbed for 10 years after treatment. The few attributable changes that occurred in fire behaviour, drying rates, and smouldering combustion can be explained by the age of the fuelbed within that time frame (Keane et al. 2017).

In southern US pine forests, a study concluded that mastication followed by rapid shrub regeneration did not necessarily reduce the overall fuel load for long and that there is a short window of time for prescribed fire to be effective in reducing fuels after mastication treatment (Kreye et al. 2014). This was similarly noted in northern California and southern Oregon forests on a two- to five-year time scale (LeQuire 2009). Stottlemyer et al. (2015) compared mastication and prescribed burning (but did not use the two strategies in tandem) in southern pine forests affected by pine bark beetles. The authors found that the total dead and down woody fuel loading was greater in masticated plots than in burned plots, that fuelbed depth was not different, and that fuelbed bulk density was higher in masticated plots than in burned plots. Research in southern pine forests of Georgia and Louisiana suggested that mastication treatments that are used to rapidly alter the midstorey will have to be maintained with follow-up treatment, and prescribed burning is most effective (Rummer et al. n.d.).

In a western Mediterranean pine forest in Spain, the effects of mastication and other thinning treatments lasted at least five years after treatment in terms of reduced canopy bulk density, canopy fuel load, and under-canopy fuel load. Consequently, all of these effects reduced crown fire susceptibility for at least five years (Jiménez et al. 2016). In gorse shrublands of Spain, mastication and prescribed burning (separately) have been noted as feasible techniques for managing fuels while recovering the native plant community and regenerating of shrubs (Fernández et al. 2013a, 2013b, 2015).

In eastern deciduous oak woodlands, mastication and prescribed fire two years after the mastication treatment were used in isolation and together resulting in reduced 1-h and 10-h fuels from mastication only and reduced 10-h fuels when used in combination. However, the burn severity did not differ between treatments (Arthur et al. 2023). In similar upland hardwood forests, mastication alone increased 1-h and 100-h fuels on the forest floor (Black et al. 2019).

2.c. Risk Management Strategies to Address Hazards

Mulching

Hsieh et al. (2019) tested six types of mulch products (raw wood chips, compost mulch, bark nuggets, medium bark mulch, cedar mulch, and rubber mulch) in a laboratory environment to determine the fire danger associated with different landscaping options. Using the match drop method, oven-dried mulch products were tested and compared for rate of spread, average flame length, and number of matches (up to three) before successful ignition. The authors found that compost mulch showed the lowest fire intensity factors. They also stated that "cedar mulch, raw wood chips, and rubber mulch should not be considered because of their high ignition probability and volatile fire behaviour" (Hsieh et al. 2019). All mulch types tested showed a high probability of ignition; however, the data showed that bark nuggets and medium bark mulch have a somewhat lower probability (Hsieh et al. 2019).

Schiks et al. (2016) recommended designing mulch treatments that ran along an east-west orientation to reduce drying impacts from solar radiation on generated fuel. The authors also proposed partial harvest systems to maintain some canopy cover through inter-tree spacing (rather than strip mulching). This way, the amount of rainfall reaching the forest floor is greater, and smaller rainfall events will have more impact on the moisture content of duff and mulch. However, these influences vary depending on localized rainfall events (Figure 8). The authors noted that where infrequent, large rainfall events occur, mulching intensity may be reduced compared to areas with frequent, small rainfall events. Moisture content and mulch temperature will influence the behaviour of a prescribed fire; therefore, Schiks et al. (2016) recommended using infra-red cameras to monitor surface temperature during burning operations.

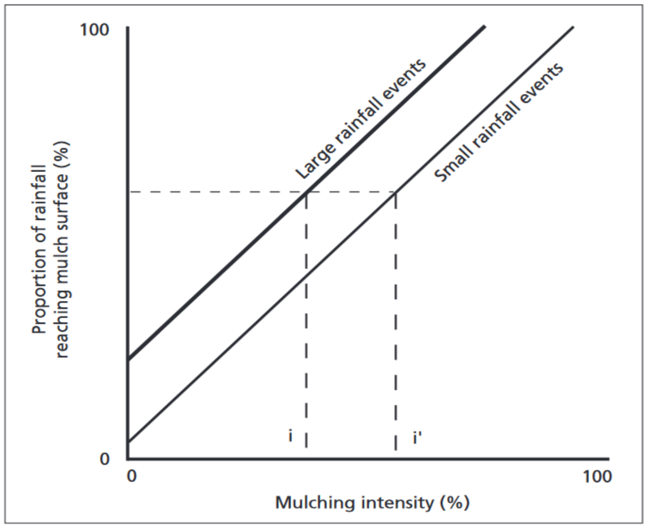


Figure 6. Conceptual diagram showing the relationship between mulching intensity and the ability of a rainfall event to increase surface fuel moisture. Greater mulching and/or thinning intensity (indicated by i' relative to i) is required to achieve the same increase in rainfall reaching surface fuels in a climate with smaller average rainfall events.

Figure 8. Influence of rainfall events (Figure 6 from Schiks et al. [2016]).

Mastication

Sikkink et al. (2017) noted differences in fire behaviour on dry sand versus dry duff. Fuel load is the most important factor to consider on dry sand, whereas the duration of flaming and smouldering is more relevant on dry duff. The authors recommended assessing the soil substrate before burning masticated fuelbeds as it will influence burning duration and temperature, which can impact suppression (Sikkink et al. 2017).

2.d. Fire Behaviour Modeling

2.d.i. Chipped fuelbeds as a novel fuel type

Chipping

Hvenegaard (2013) compared the model outputs of three fuel types (O-1b, S-3, and C-5) to actual observed fire behaviour (Table 14). Fuel type O1-b overestimated the rate of spread and head fire intensity, while the C-5 fuel type underestimated both. The S-3 fuel type accurately predicted the rate of spread but overestimated head fire intensity (Hvenegaard 2013).

Table 4. Comparison of observed fire behaviour on September 6 and predicted fire behaviour.

Time of Ignition	Initial Spread Index	Buildup Index	Observed NTL ROW		Predicted 5L61 ROW		Predicted S-3		Predicted C-5	
			ROS	HFI	ROS	HFI	ROS	HFI	ROS	HFI
1328	1.9	27	.26	30	2.1	117	.13	525	.01	.75
1425	2.0	27	.32	40	2.3	127	.15	613	.01	.91
1540	3.3	27	1.5	180	4.6	255	.50	1988	.04	4.0

**ROS is measured in m/min and HFI is measured in kW/m.*

Table 14. Observed vs. modelled fire behaviour (Table 4 from Hvenegaard [2013]).

Mulching

Battaglia et al. (2010) suggested that an altered stand structure will likely decrease the active crown fire hazard in closed-canopy forest types. However, they found that modelling crown fire regimes was difficult as it depended on custom fuel models based on surface fuelbed characteristics, which differ from those of the untreated counterparts at mulched sites. Therefore, the authors could not predict active or passive crown fire behaviour due to missing parameters in the fire models, including fuel load, fuelbed bulk density, surface-to-area volume ratio, and fuel size class distribution (this study took place in 2010, however, and fire models have since been updated). The authors concluded that surface fuel load in mulched areas could nevertheless be estimated from fuelbed depth and coverage measures, findings that were similar to those in a previous study by Battaglia et al. (2009). This would be an easier technique for managers to use in the field.

Hvenegaard and Price (2018) noted that characterizing mulch fuelbeds is difficult as each one differs depending on the site conditions and the specific treatment details. Information such as mulch fuel size, shape, distribution, age, bulk density, and mix with other fuels (both live and dead) must be considered as these factors will result in different fire behaviour. The authors mentioned a need to characterize the fuel type to be an “identifiable association of fuel elements” with a range of variables (size, species, arrangement, form, continuity, etc.) that make fuelbeds unique (Hvenegaard and Price 2018).

Mastication

Kreye (2012) expanded on the modelled results of Kobziar et al. (2013) using BehavePlus and found variation between observed and predicted fire behaviour. Flame length and rate of spread were overpredicted, and only fireline intensity in untreated sites showed better predictability. These results were attributed to difficulties with quantifying fire behaviour in shrub fuels and in areas with heterogenous fuel depths, and Kreye (2012) mentioned that using models for predicting fire behaviour in masticated sites may be limited where dense surface fuels exist beneath a shrub later, as such areas tend to generate localized heat for longer periods. The author also stated that models developed for masticated fuelbeds need to account for the heterogeneity of the forest floor, such that predictions for soil heating can be more accurate.

Schiks and Wotton (2015b) used the hourly FFMC model, the National Fire Danger Rating System 1-h and 10-h fuel moisture models, and a masticated surface fuel model developed by the authors in a previous study called the MAST model. They found that components of the fire weather index and the

National Fire Danger Rating System were not useful in predicting sustained flaming in masticated fuels that lack a canopy or understorey layers. The MAST model was the most accurate weather-based model but was developed specifically for mulched fuels by Schiks and Wotton (2015b). This model is like the FFMC, as it predicts fuel moisture, but it differs by modifying six elements of the hourly FFMC formulas to better account for masticated fuelbed moisture. These modifications include:

1. The maximum moisture content was 150%.
2. The assumed fuel load and bulk density for the fuel layer were higher.
3. The predicted fuel temperature from fuel-specific constants was derived from observations in the field.
4. The relative humidity in the pore space was dependent on fuel temperature.
5. The equilibrium moisture content was for wood.
6. The response time was scaled to wood particles.

From these elements, moisture can be predicted for the upper 2 cm of masticated fuelbeds (Schiks and Wotton 2015b). Though not included in the FFMC model, fuel temperature was included in the MAST model as the authors assumed it played a significant role in the drying process of masticated fuels. They found that the FFMC overpredicts fuel moisture and that the masticated fuels (called *mulch* in the study) tend to be much drier (Schiks and Wotton 2015b). This overprediction was related to the lack of solar radiation in the FFMC when compared to MAST models. The authors recommended including solar radiation in fuel moisture models even when fire weather stations do not provide such information. To do so, they recommend that using a solar radiation model, developed from latitude, longitude, day of year, and time of year, be coupled with a model that estimates attenuation of radiation by atmospheric moisture; the authors provided an equation in their results (Equation 16 – not shown) (Schiks and Wotton 2015b).

Using the MAST model was further explored in another study by Schiks et al. (2015), in which the authors investigated moisture trends through a masticated fuelbed profile, rather than just the top 2 cm. They installed weather stations in each plot that had a multi-channel datalogger, a shielded temperature and relative humidity sensor, a two-dimensional sonic anemometer, a tipping bucket rain gauge, and a solar radiometer (Schiks et al. 2015). Air temperature, relative humidity, 10 m wind speed, and precipitation were also collected from a nearby remote weather station, to be used for the fire weather index.

Heinsch et al. (2018) used BehavePlus (version 5.0.5) to estimate fire behaviour for laboratory burns in masticated fuelbeds. The authors used Rothermel fire spread model for rate of spread and Byram's equations for flame length. Moisture codes were measured from material taken from sites (which was then oven dried). The actual rate of spread and flame length from the experimental burns were compared to those from three standard models (SB1, SB2, and logging slash) and from five custom fuel models specifically designed for masticated fuels (Heinsch et al. 2018). Wind was not included in the study, and fabricated slopes were low, so the authors used flame height as a measure for flame length. The experimental burns had an average rate of spread of 0.1 m/min and average flame height that ranged from 0.2 m to 0.4 m (Heinsch et al. 2018). Flaming combustion was short, lasting <30 minutes; smouldering may have continued for much longer, though it was not reported on in the study. Except in fuel model SB2, the modelled rate of spread and flame length of 0.6 m/min and <1.2 m, respectively, were close to the observed values.

Heinsch et al. (2018) provided general results from the experimental burns that could not be predicted by the models, including the following:

- Fuelbeds with large (100-h and bigger) fuels burned longer, but larger pieces tended to restrict fire spread, igniting only from smouldering once the flame front passed.
- Fire spread was facilitated by 1-h and 10-h fuels, while larger fuels facilitated continued burning after the flame front passed.
- Smouldering tended to continue for one hour after flames were extinguished.
- The rate of spread and flame length (height) increased as the fuelbed burned (fires did not reach steady-state conditions).
- The method of mastication showed some influence on burning: the material from chipped and mowed sites never burned the full length of the laboratory fuelbed (hindering the authors from estimating fire behaviour).

Jain et al. (2012) reviewed fuel management practices in northwestern US. Since mastication processes can leave a wide range of piece sizes across a site, modelling fire behaviour for masticated sites is difficult. Integrated assessment modelling can be useful for multi-objective planning, as it can include many important factors, such as fire and fuel treatments, vegetation, watersheds, fisheries, soils, wildlife, aesthetics, economics, social considerations, air quality, and threatened and/or endangered plant species.

2.d.ii. Metrics for model input and measurement

Mulching

Battaglia et al. (2009) used the Fire and Fuels Extension to the Forest Vegetation Simulator to estimate bulk density and canopy base height, and measured crown length and tree height directly in plots. For treated and untreated plots, carbon stocks were modelled for 25 years in the future. Custom models were created to estimate various parameters (soil heating, smoke output, tree mortality, and fuel consumption), with plans to conduct burns to verify the models. The validation burns did not occur due to uncooperative weather. Additional modelling was completed in BehavePlus, but with little success, as the model was too sensitive to fuelbed bulk density and the surface-area-to-volume ratio (Battaglia et al. 2009).

Battaglia et al. (2010) also used the Fire and Fuels Extension to the Forest Vegetation Simulator to determine canopy bulk density and base height in their treatment areas. Additional variables, including tree height, crown length, and crown width, were measured to model tree biomass. Typically, to model active crown fire behaviour, the surface fire rate of spread and intensity must first be calculated. However, the authors found that the fuel models used to calculate surface fire behaviour did not sufficiently capture the mulched fuelbed characteristics. They recommended that additional parameters, such as fuel load, bulk density, surface-to-area volume ratio, and fuel size distribution, be included in models and validated with experimental burns to provide more accurate estimations (Battaglia et al. 2010). Battaglia et al. (n.d.) provided a brief overview of measuring mulch fuel load using depth in a document entitled *Measuring mulch fuelbed loads*, which Battaglia et al. (2010) used and showed as being effective for estimating. This methodology could be used to measure mulch more efficiently in treated stands.

Mastication

Kreye (2012) compared modelled versus observed fire behaviour using BehavePlus and found high levels of variation between values. In the model, Rothermel fire spread equations were used for rate of spread, flame length, and fire intensity prediction, which required plot data for fuel load, moisture, and weather conditions. These inputs were generated by measuring vegetation (overstorey, shrubs, and surface fuels), tree height, DBH, basal area, and quadratic mean height of all trees in the plots. Shrub biomass was estimated from measurements in two 1 m by 4 m transect belts, and litter depth, duff depth, and surface fuels were measured across 10 m transects. Only litter and 1-h fuel inputs were used in the custom model, and their post-fire consumption was used to calculate the observed fire intensity. Fuelbed depth was assessed using average shrub height and live woody fuel load (total shrub foliar biomass). Compared to the observed fire, the predicted flame length was higher in masticated sites and lower in untreated areas, which Kreye (2012) attributed to where flame length measurements begin. In the model, flame length is measured from the top of the fuelbed to the tip of the flame (in this case, the shrub height), whereas in the field, flame length was measured by vertical flame height and angle from the litter surface. The author recommended measuring flame length from above the forest floor (litter fuelbed) as a better metric to assess fire controllability during prescribed fires. The rate of spread was also overestimated in the models, but fire intensity appeared to yield similar values (Kreye 2012).

Schiks and Hvenegaard (2013) collected mulch moisture, air temperature, relative humidity, wind speed, FFMC, and initial spread index values as predictor variables for their ignitions model in masticated fuelbeds (the term *masticated* was used to describe both chipped and mulched fuels). The authors found that mulch moisture was the best predictor for the probability of ignition but that measuring this variable directly was difficult as equipment can be variable and oven-drying methods are not operationally feasible (Schiks and Hvenegaard 2013). Models that use the fire weather index and the hourly FFMC can predict upper mulch moisture to a certain extent (Schiks and Hvenegaard 2013), which can be used where more intensive moisture tracking cannot occur.

Heinsch et al. (2018) found no relationship between time since mastication and fire behaviour, at least not within a 10-year time frame. The authors noted no apparent decomposition of fuels at sites of this age, though they mentioned finding more rotted material where masticated fuels were older than 10 years, remarking about a potential for different fire behaviour that was not studied in their report. The method of mastication had some influence on fire behaviour: chipped and mowed sites burned incompletely compared to sites that were masticated using rotating or horizontal drum heads. The authors could measure fire behaviour only across similar fuel moistures in their study and did not include live fuels in the constructed fuelbeds, which is a required input for two of the custom models they used. Therefore, they used a live woody fuel moisture value of 150% to represent foliage and new growth in masticated sites. Though smouldering was observed in their experimental burns, the authors could not predict residual burning with the current models, which may be a major limitation in estimating fire suppression efforts in masticated fuelbeds, especially where wind plays a role in reignition (Heinsch et al. 2018).

Keane et al. (2018) measured three-dimensional variables at the particle scale, including length, width/diameter, and height. Length was the longest axis on a piece of masticated material, width was the greatest distance across a particle, and height was the thickness of the piece where diameter could not be measured (when pieces were not round). These metrics were combined with general shape to calculate particle volume, which was then used to find particle density and the surface-area-to-volume ratio (Keane et al. 2018). Table 15 and Table 16 show diagrams and descriptions of the common shapes of masticated debris that were used to calculate volume and surface area. However, the authors noted that the process of calculating these variables was coarse and costly, and complex shapes were often ignored.

Hood and Wu (2006) proposed a cover–depth method for estimating masticated fuel depth, arguing that the older planar intercept method might be inaccurate as it assumes that all fuel pieces are round. The cover–depth method involves placing 1 m^2 quadrats along a fuel transect and estimating the percent cover of the fuelbed and the masticated/woody fuelbed, measuring depth to mineral soil, and estimating percent of different fuel types in the vertical profile (masticated/woody litter). Loading can then be estimated by multiplying the estimated bulk density by fuelbed depth and cover class.

Prescribed Fire

Beverly et al. (2009) modelled fire susceptibility and the impact of prescribed fire on fire susceptibility in a large landscape using Burn-P3. The following variables were used: landscape cover type, topography, ignition pattern, fire zone, weather zone, fire season, minimum fire size, escaped fire rate, ignition rules, fire weather record, number of escaped fires, hours of burning, and spread-event days. The models indicated that prescribed fire resulted in lower fire susceptibility.

Table 5—Description and illustration of the 13 shapes chosen to estimate volume and surface area of masticated woody particles.

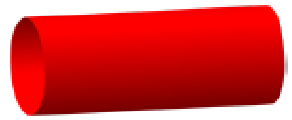
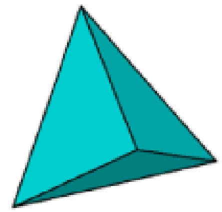
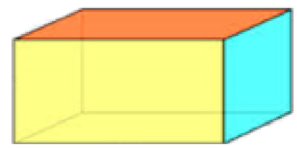
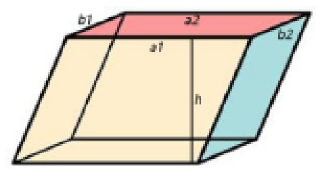
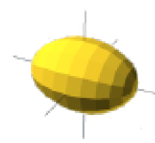
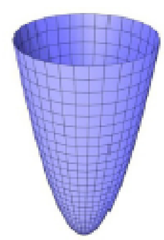
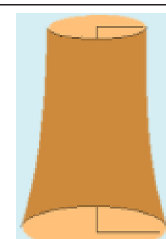
Shape	Description	Diagram
Cylinder	3D circular polygon, usually with varying widths along length. Represented by complete branches >6.5 mm long. Circular cross section	
Pyramid	3D polyhedron with four faces and three prominent sides; angles off each vertex vary. Triangular cross-section.	
Rectangular parallelepiped	3D polyhedron with six faces and four prominent sides; adjacent sides of unequal length; angles close to 90° at each vertex. Rectangular cross-section.	
Parallelepiped	3D polyhedron with six faces; faces are parallelograms lying in pairs of parallel planes; four prominent sides, angles not 90° at each vertex. Varying lengths of sides can result in equilateral, trapezoidal, rhomboidal, kite-like, or trapezium sub-shapes.	
Ellipsoid	3D polygon with plane surfaces that are all ellipses or circles, no faces, no distinct sides; ends tapered; egg shaped. Elliptical cross-section.	
Elliptic paraboloid	Quadratic surface shaped like cup or bowl; no faces; edge surface curved to ground with no outward flares at base.	
Neiloid frustrum	Quadratic surface shaped like the lower portion of a tree trunk; no straight faces, edge surface curved to ground with outward flares; top usually shaped as in elliptic paraboloid (above) but lower edge flares like tree trunk base.	

Table 15. Chip shape for fuel load estimation (Table 5 from Keane et al. [2018] [1 of 2]).

Shape	Description	Diagram
Semi-cylinder	3D polygon with no faces; two sides (one curved, one flat); one-half of a cylinder.	
Wood chip	Thin, small pieces of wood greater than 6.5 mm long but less than 3.0 mm thick; classifies as 1-hour size class.	
Wood ribbon	Pieces of wood greater than 6.5 mm long, very flexible, and various widths; flexible enough to twist and turn without breaking.	
Bark ribbon	Pieces of bark greater than 6.5 mm long, very flexible, and various widths; similar to wood ribbon, it is flexible enough to twist and turn without breaking.	
Bark piece	Pieces of bark greater than 6.5 mm but less than 25 mm at longest point; inflexible; 1-hour and 10-hour size classes combined.	
Bark chunk	Pieces of bark greater than 25 mm but less than 75 mm at longest point. Thickness varies. 100-hour size class.	

Table 16. Chip shape for fuel load estimation (Table 5 from Keane et al. [2018] [2 of 2]).

2.e. Familiarity with Fuel Type and Use in Suppression Plans as Potential Control Lines

Chipping

Hvenegaard (2013) described a single firefighter equipped with a backpack pump being able to contain points of ignition on a chipped fuelbed. The same firefighter also extinguished the fire completely using the pump as burn depth was minimal. In the same chipped bed, it took two crew members to contain line ignitions; this was attributed to increased fire size and intensity (Hvenegaard 2013).

Mulching

Hvenegaard and Price (2018) encountered high-intensity fire behaviour during a point ignition trial on mulched fuels; they observed fire whirls and spotting of up to 80 m. They noted that fire control with backpack pumps and 5/8-inch hoses was difficult, and that Hanson nozzles were more effective than fog nozzles. Both of these nozzles were tested during the fire event and were attached to a WATERAX MARK-3 pump and 1.5-inch hoses. After the first prescribed fire, crews spent approximately 1 hour wetting a 2.5 m wide strip of mulched fuel around the burned area to prevent fire spread, encountering increased smoke in the process. They concluded that a large volume of water is required to properly extinguish mulched fuels. They also found that previously burned mulch could reignite with firebrand spotting, supporting increased fire spread in areas that had been treated (Hvenegaard and Price 2018). This points to a need for enhanced fuel consumption, either through intense prescribed fire or repeat treatments, to thoroughly mitigate the fire risk in mulched fuelbeds.

Hvenegaard (2017) experimented with mulching grids in jack pine and black spruce forests in the Northwest Territories, where 4 m by 6 m mulched grids left residual clumps of non-thinned trees. Five years after treatment, experimental fire was applied to the treatment unit by starting ignitions in the untreated forest adjacent to the treatment unit. Fire intensity in the treated forest (6,000–8,000 kW/m) would challenge fire suppression crew direct attack, although attacking the fire at its flanks instead could be safer and more effective. Notably, the author remarked that aerial suppression of a fire of that intensity would be successful. The author also noted that the wide mulched strips could provide firefighter access to complete direct suppression. Further, anecdotal evidence indicated that by wetting the mulched fuels with sprinklers ahead of fire spread, fire behaviour would likely decrease when spread occurred, improving the ability of firefighters to respond safely and directly.

Mastication

Heinsch et al. (2018) mentioned the importance of ensuring complete fire suppression in masticated fuelbeds as smouldering can persist and flames reignite under changing weather conditions. Crews may have difficulty fully assessing deep fuelbeds for smouldering, so the authors recommended extended fire watches and patrols after fires to monitor for reignition.

Stephens et al. (2009) reported on the impacts of fuel treatments on fuel load and potential fire severity in five study areas throughout western US. The forests studied were either ponderosa pine dominated or mixed conifer. Fuel data was collected and modelled using FMAPlus to assess fire behaviour under the 80th, 90th, and 97th percentile weather conditions. The authors compared fuel treatments that mechanically thinned the forest, paired mechanical thinning with burning, or only burned the forest. One study site incorporated mastication to treat branches and tops of commercial trees and small trees. This increased the fine fuel load (diameter <7.5 cm) from an average of 1.42 kg/m^2 in the control plots to 1.71 kg/m^2 after thinning and mastication. Mechanical treatments alone at this site generated little improvement in passive crown fire potential (torching index), and potential tree mortality increased for trees with DBH <51 cm under the 80th percentile conditions or stayed the same for other sizes of tree classes. However, the overall crown fire potential was still reduced due the thinning of small trees, which increased the residual canopy base height. Burning this site further reduced crown fire potential because it reduced fine fuels significantly (average of 0.48 kg/m^2 after burning).

3. Interactions with Prescribed Fire: Objectives and Impacts

3.a. Rationale of Burning After Treatment

Battaglia et al. (2009) stated that vegetation response may be positive or negative depending on the objectives of mulching. Reducing fuel without a follow-up treatment may be negated by shrub growth after mulching, but vegetation may be beneficial if fire is going to be used in the system after mulching. Prescribed fire after mulching results in greater surface fire behaviour (Battaglia et al. 2009, 2010) and the consumption of 1-h and 10-h fuels.

Frame (2011) noted that mulching treatments (chipping and mastication) as part of debris management were cost-effective solutions that avoid the production of smoke from pile burning and the hauling costs associated with biomass removal off site.

Gray and Blackwell (2016) performed a study in Douglas-fir and ponderosa pine stands in BC, in which they thinned, thinned and mulched, and thinned and removed debris from sites, and all areas underwent a prescribed fire after the treatment. In the thinned and thinned + mulched sites, the amount of surface fuels was higher, whereas the thinned + removed sites had a lower pre-burn fuel load that would enable safer implementation of a prescribed fire (Gray and Blackwell 2016). Additionally, where prescribed fire was used without any prior fuel treatment, the authors noted an increase in post-burn surface fuel load due to fire-caused mortality (windthrow, crown scorch, beetle infestation, etc.). This suggests that mechanical fuel treatments preceding a prescribed fire are better than a prescribed fire alone, but that the method of mechanical treatment will influence how the prescribed fire behaves in the stand.

Though this was not the purpose of the study in Hvenegaard (2019), the author found that low intensity mulching treatments that leave more intact roundwood and do not incorporate the duff layer resulted in lower fuel load than mid- and high-intensity treatments (Table 17) (Hvenegaard 2019). More research is required, but it is possible that low intensity mulching treatments could be used in dense stands that require an initial fuel treatment, resulting in higher operational productivity and reduced surface fuel load compared to standard mulching operations.

Table 2. Post-treatment debris loading

Subunit (mulching Intensity)	Mulched debris loading (tonnes/ha) and percentage (%) of total					
	Diameter size class (cm)					Overall loading
	Litter and SC1 (0.00– 0.49)	SC2 (0.50– 0.99)	SC3 (1.00–2.99)	SC4 (3.00–4.99)	SC5 (5.00–6.99)	
2A (low)	32.9 (54.8)	7.8 (13.0)	8.2 (13.6)	9.3 (15.4)	1.9 (3.2)	60.1 (100)
2B (normal)	96.9 (58.3)	28.2 (17.0)	32.8 (19.8)	8.2 (4.9)	0.0	166.1 (100)
2C (high)	64.7 (69.1)	13.1 (14.0)	14.6 (15.5)	1.3 (1.4)	0.0	93.7 (100)

Table 17. Mulched debris loading (Table 2 from Hvenegaard [2019]).

Kobziar et al. (2013) made a point that mechanical treatments, such as mastication, will likely be prioritized in fire-suppressed ecosystems, but that the increase in surface fuels resulting from such treatments may increase the ignitability of the forest floor and potentially result in overstorey mortality. The authors recommended burning when surface fuels are dry, but duff is moist enough to limit tree damage from smouldering, which results in a very limited window for prescribed fire. Where prescribed fire is not planned as a follow-up treatment, the risk of wildfire may be increased as the fuelbed dries and as shrubs return to the previously treated sites (Kobziar et al. 2013).

Where mechanical treatments are planned for subsequent prescribed fire, Marshall et al. (2008) noted off-site problems, such as cost, access, and productivity, as the more important considerations for fire planning. For this reason, combining mechanical and prescribed fire treatments may reduce the costs associated with each treatment. These include the costs associated with ensuring that roads are capable of supporting the equipment needed for both operations and that bridges can support the weight of the equipment (Marshall et al. 2008). Another major issue where prescribed fire is used as a follow-up treatment is timing because the schedule of the burn is dictated by weather windows. If a site is burned in winter, fire intensity will be lower; in this scenario, the consumption of debris may be smaller, but there will be less impact on resprouting vegetation. If done in the spring, fire will reduce the amount of revegetating material; if done too late in the season, the return of live fuels may or may not hinder the effectiveness of the fire through increased moisture (Marshall et al. 2008).

In a laboratory prescribed fire on masticated fuels, Thompson et al. (2016) suggested that the combustion of masticated fuelbeds would be an effective way to store black carbon in well-drained, sand-containing soils, such as those found in pine and aspen stands in boreal forests. The authors mentioned this as a benefit of burning in masticated fuelbeds to promote better carbon sequestration. They recommended including larger fuels (up to 3 cm in diameter) in masticated fuelbeds planned for prescribed fire to reduce flaming intensity and fuel moisture (above 20% in deeper horizons), which would result in less rigorous combustion and increase carbon residuals (such as pyrogenic carbon).

Keane et al. (2018) argued against mastication in dry forest types that may not undergo decomposition until a decade after treatment; this was based on a lack of significant difference in physical and chemical characteristics in their ponderosa pine study sites over 10 years. They suggested burning sites rather than masticating them as "the longer a masticated fuelbed remains intact, the higher the potential for unwanted high-severity fire that may cause uncharacteristic severe damage to the stand" (Keane et al. 2018).

Glitzenstein et al. (2006) concluded that chipping or using other forms of pre-treatment on burn areas was not required to make prescribed fire safe in Francis Marion National Forest, South Carolina. They also stated that prescribed fire could be undertaken in similar ecosystems when treatment had not been carried out for at least 14 years if the site and weather conditions were favourable.

Yukon Wildland Fire Management (2022) conducted a prescribed fire after a mastication operation. The authors took over 100 measurements and determined that the average remaining fuelbed depth was 3.25 cm. Using this and previous measurements, they determined that 4.01 cm of masticated fuel was consumed during the prescribed fire, which equated to 811.5 t (55.24%) of material consumed across the whole treatment area and 657.5 t remaining (Yukon Wildland Fire Management 2022). There were only a few hot spots or areas of long-term smouldering, which countered the authors' original hypothesis. Only the top layer of fuel was depleted, and much of the compacted material at the bottom of the fuelbed remained undisturbed (Yukon Wildland Fire Management 2022).

Gray (2011) advocates for following mastication treatment with prescribed fire in ecosystems that exhibit slow woody fuel decomposition, such as dry forests in BC. In the study, trees with DBH <20 cm were mulched and pulverized into small particles. However, the treatment resulted in a significant increase in larger fuels (>2.5 cm) relative to smaller fuels, as almost 5,000 stems per hectare were converted into surface fuel. Before a prescribed fire could be applied to the masticated fuels, the fuelbed changed dramatically from a pure masticated fuelbed to a mixed masticated and herbaceous fuelbed due to increased solar radiation to the forest floor. This changed the burn plan from the anticipated slow-moving fire associated with a low, compacted masticated fuelbed to a potentially fast-moving fire associated with a tall, porous herbaceous fuelbed of fine fuels. Based on these factors, implementing the burn plan was held off until conditions were suitable to achieve the objectives. By burning under these conditions, the prescribed fire consumed significant amounts of medium and large wood particles at a slow rate of spread. Consumption was the main goal of the prescribed fire in this study, so it was deemed a success.

Stephens and Moghaddas (2005) conducted an experiment in which the end goal was to modify tree stands so that 80% of the trees would survive a wildfire (modelled at the 80th percentile of weather conditions). Plots that were treated mechanically (thinning the trees and then masticating the undergrowth) significantly increased the 1-h, 10-h, 100-h, and 1000-h fuel load and fuel depth. Because logging slash in the 100-h and 1000-h size classes in the Sierra Nevada forests was still present 20–30 years later, the authors speculated that increased surface fuels from mastication might persist for decades. Plots that included burning (thinning + mastication + burning, or burning only treatments) significantly reduced the total combined fuel load (litter, duff, 10-h, 100-h, and 1000-h fuels) by up to 90%. These treatments were predicted to reduce fireline intensity, flame length, and rate of spread up to the 90th percentile weather conditions. All treatments significantly moderated fire behaviour, but the mechanical only treatment reduced fire behaviour the least.

Ohlson et al. (2006) designed a multi-attribute, trade-off analysis model to compare different types of fire reduction techniques. The study area near Cranbrook, BC, was divided into polygons (using GIS data) that represented historical natural fire regimes, or the fire regimes used under current climactic conditions but before Europeans arrived in Canada. These polygons were reclassified into present-day condition classes, which reflected the degree of change in historical stand structure and fuel loading by considering the effects of harvest, fuel treatments, wildfire, and natural succession. The model included biophysical and ecological considerations, socioeconomic factors, and policy and institutional goals for a plot of forest in southeastern BC. The model compared mechanical treatments (all materials removed) with mechanical treatments followed by prescribed fire. In the second case, harvestable timber was removed, and the remaining materials were burned at the sites. Follow-up burns at those sites were anticipated for the future. The model suggested that mechanical treatment followed by prescribed fire would be less costly than regular mechanical treatments and has the advantage of increasing landscape biodiversity, increasing ungulate forage area, decreasing wildfire emissions, and decreasing property damage. However, it would likely lead to increased wildfire suppression costs, a decreased volume of harvestable timber, decreased ungulate cover area, decreased local air quality (because of smoke from prescribed burning), and decreased stored carbon in the forest. As a note, the study was not trying to pick best management practices; instead, it highlighted the types of data that can be generated by a multi-attribute, trade-off analysis model for decision-making.

In an article for the *British Columbia Forest Professional* magazine, Gray et al. (2010) stated that machine mastication holds promise as a fuel treatment option in situations where prescribed fire is not possible and in those in which it is a pre-prescribed fire treatment. Mastication is especially useful for the treatment of small-diameter trees by treating them in place and reducing costs compared to manual slashing, pile burning, slashing and chipping, or mechanical thinning and removal. Gray et al. (2010) reported that if the masticated fuelbed is left to decompose without prescribed fire, the threat of increased burn severity exists before the material decomposes. In wetter forests, decomposition rates will be faster than in forests with lower soil moisture. The primary wildfire concern with masticated fuelbeds is the smouldering combustion at moderate to high temperatures, which negatively affects soil organisms and the structure and chemical composition of soil. However, burn severity decreases with reduced fuelbed depth and increased soil moisture, so reduced fuelbed depth can mitigate concerns related to high burn severity. Additionally, smaller wood particles decompose faster than larger wood particles, so decreasing the size of the fuel particles increases decomposition. Gray et al. (2010) concluded, masticating fuels is a good stand-alone treatment in ecosystems with high decomposition rates, such as the warm, moist ecosystems of southern Vancouver Island, the Gulf Islands, the Coast-Interior transition zone, and the West Kootenays. In drier ecosystems, mastication fuel treatments are best used as a pre-treatment for subsequent prescribed burning operations.

Jain et al. (2012) reviewed fuel management practices in northwestern US. Prescribed fire in masticated fuelbeds causes high scorch height on residual trees. Thus, to prevent tree damage, prescribed fire should be conducted in cool temperatures or when wind speeds can disperse heat horizontally. Thompson et al. (2016) recommended waiting for optimal conditions, such as during late summer, to increase consumption, but they also suggested burning on cloudy days with moderate humidity to increase surface moisture content and reduce flaming intensity. In California, mastication combined with prescribed fire resulted in higher average maximum temperatures in aerial, litter, and soil layers compared to unmasticated plots, which caused higher mortality of deciduous and coniferous trees, and shrubs (Bradley et al. 2003).

3.b. Anticipated Smoke Production

Lyon et al. (2018) noted that masticated fuelbeds tend to be largely combusted through smouldering, which may increase the release of fine particulates relative to flaming combustion. Morgan et al. (2018b) cautioned of greater emissions of smoke that contains particulates, and of embers, both of which could increase the rate of spot fires. Both are attributed to greater smouldering that occurs in masticated fuelbeds (Morgan et al. 2018b).

In a study in South Carolina, models and field observations indicated that significantly less smoke was released during prescribed fire in areas that had received chipping treatment compared to areas that had not been treated (Glitzenstein et al. 2006). However, the authors noted that smoke release may have simply been delayed until a later prescribed fire or wildfire in chipped plots in which less area in general had been burned, as opposed to ultimately reduced. Chipped and unchipped plots had similar fuel moisture levels during this study (Glitzenstein et al. 2006).

In Australian eucalypt forests, masticated fuelbeds were sampled and burned in the lab. The study revealed that smouldering and flaming duration increased significantly in masticated plots due to greater amounts of fine and coarse fuels in a masticated fuelbed, but that such changes would be reduced over time (four years in this study) (Cawson et al. 2021). Further investigation into this topic is warranted.

3.c. Ecological Impacts

Morgan et al. (2018a) reported tree growth to be slower in areas where fires burned in masticated fuelbeds due to higher fire intensity. Walker et al. (2012) documented that understorey shrub abundance was diminished by prescribed fire in chipped fuelbeds and did not recover over the course of one to three years after the fire. Walker et al. (2012) reported that these findings reflect those in some studies in western US forests but are in discord with others, in which the understorey shrub recovery to pre-fire conditions was almost complete after a similar time period. Yukon Wildland Fire Management (2022) reported that after a prescribed fire in a mulched fuelbed, there was significant blowdown of stems not masticated because tree roots had been damaged during the fire.

The study by Nesmith et al. (2010) showed an interaction between blister rust (*Cronartium ribicola*) infection and pitch production on tree stems with charring, noting that raking around the base of a tree could indirectly reduce charring where blister rust is a concern. Reduced charring could then decrease the likelihood of beetle attacks, which tend to be facilitated in weakened trees after prescribed fire (Nesmith et al. 2010).

3.d. Data Collection

Hsieh (2020) performed a study analyzing the effectiveness of retardant on fires in mulched sites. In an aspen-dominated stand, Phos-Chek LC-95A-R fire retardant was spread across plots using garden watering cans and was allowed to dry in all but one plot, which would remain wet during the fire to see whether differences arose. The results showed that the retardant was effective for reducing fire intensity on mulch, but not for extinguishing the fire. However, these findings were attributed to plot size more so than retardant effectiveness; Hsieh (2020) stated that further study was needed in larger areas and more control of fire passage is needed between plots. The author concluded that wet retardant was more effective at reducing fire intensity than dry retardant.

4. Environmental Concerns and Interactions

4.a. Ecological Interactions with Treatments

Chipping

Baxter (n.d.) reported from survey responses that replanting was most difficult in areas where debris was left on site, and this added to the costs of the planting efforts. Chipping and piling was ranked three of four (four being the worst) of all four treatments and was found to be only marginally better than just leaving debris on site (Baxter n.d.). Kabzems et al. (2011) reviewed studies on the impact of chip application on soil and vegetation in North America. They reported that chip piles deeper than 10 cm can minimize efficiency in planting seedlings and can increase the suppression of natural regeneration of trees. In central BC, lodgepole pine seedlings under 5–10 cm of wood chip mulch on treated landings were significantly smaller in stem volume after three years than those on untreated landings after three years. They also found studies done in eastern Washington that reported poor growth and survival of Douglas-fir and lodgepole pine seedlings on chipped woody debris plots compared to treatments in which debris was left intact or was removed from the site. Comparatively, aspen wood chip mulch 5–10 cm deep in Alaska reduced foliar nitrogen concentrations in white spruce seedlings but increased foliar potassium. However, there were no nutrient disorders in lodgepole pine seedlings, and foliar nutrient concentrations did not vary significantly among the treatments. Surface mulch treatments of 10 cm in depth made no difference in lodgepole pine growth on rehabilitated landings in the Okanagan region after eight years. Aspen logging slash and chips are known to reduce aspen regeneration, delay sucker emergence, and reduce aspen growth. Specifically, aspen regeneration density is reduced by 30–50% with a chipping residue depth of 4–10 cm. The reasons for this may be the cooler soil conditions and the physical barrier created by chipping.

Kabzems et al. (2011) also described the effect of wood chips on forage production. They reported that the depth and distribution of chipped biomass in the forested landscapes of southwestern US had significant impacts on the understorey plant community, reducing plant cover, diversity, and species richness. The authors stipulated that the physical barrier of wood chips may be more important than the soil nitrogen effects for understorey plants. In some cases, native shrubs increased in cover after wood chipping treatments that averaged 7.5 cm in depth.

In Walker et al. (2012), mechanized thinning with a cut-to-length harvesting system followed by chipping and prescribed fire was assessed for its impact on understorey shrub communities in the mixed conifer forests of the Sierra Nevada. The authors found that the mechanized operations had minimal detrimental impacts on undergrowth cover and weight. For two species, prostrate ceanothus (*Ceanothus prostratus*) and creeping snowberry (*Gaultheria hispidula*), the treatments were stimulatory. When prescribed fire was implemented, understorey loss was pronounced, especially in huckleberry oak (*Quercus vacciniifolia*), which was the most prevalent species on site. Additionally, neither the prescribed fire at the control site nor the prescribed fire at the thinned and chipped site caused the reintroduction of grasses and forbs to the understorey composition, which is usually a goal of restoration efforts in western US forests. The authors concluded that the greatest understorey re-establishment after the thinning, chipping, and fire treatments occurred at sites with sufficient pre-existing rootstocks and seed banks.

Mulching

Battaglia et al. (2009) studied the impacts of mulching (used to describe both mastication and chipping) across multiple forest types in Colorado. They examined how overstorey thinning, in combination with mulching, would impact understorey vegetation. When assessing herbaceous cover, the authors found that two forest types were limited by the depth of mulch: ponderosa pine and juniper stands. Other forest types, such as lodgepole pine and mixed coniferous, had limited herbaceous cover for other reasons. Understorey vegetation was not hindered; indeed, it increased after treatments (Battaglia et al. 2009). Shrub and herb cover were not significantly different between treatments. Species richness differed in only one forest type: it increased in juniper forests after treatments. Richness was hindered in juniper stands due to the density and growth form of these species. Some forest types exhibited small increases in invasive species, but none were significant. The authors warned that further research is needed as mulched beds tended to contain more exotic species than untreated areas (Battaglia et al. 2009). The results were mixed for tree regeneration; all but lodgepole pine forests experienced lower regeneration in treated areas compared to untreated areas (Battaglia et al. 2009).

Fornwalt et al. (2017) used the same study sites as Battaglia et al. (2009, 2010) to analyze vegetation response to mulching treatments several years later. They found that mulching (used to describe mastication and chipping treatments) stimulated graminoid, forb, and shrub communities overall. Plant richness and cover increased by 40–65% and 57–69%, respectively, with the most pronounced increase occurring six to nine years after mulching. This was attributed to increased light and water availability after an opening of the overstorey. The depth of mulch had variable impacts on understorey vegetation depending on the forest type. In dry, warm forest types, the authors found that mulch depth of about 3 cm improved growing conditions to the extent that it outweighed the impacts of this suppressive ground cover (Fornwalt et al. 2017). The occurrence of invasive species had not significantly increased in the time since the treatments, and only annual and biennial species were encountered throughout the sites (Fornwalt et al. 2017). One species that may require attention, however, was Canada thistle (*Cirsium arvense*), which Battaglia et al. (2009) did not consider a major concern at the time of treatment. Fornwalt et al. (2017), on the other hand, found increases of Canada thistle by 20% in ponderosa pine stands and by 38% in lodgepole pine and mixed conifer stands two to four years after mulching. This further increased to 50% and 71% six to nine years later in treated sites and was less present in untreated areas (Fornwalt et al. 2017). This suggests that Canada thistle may benefit from the immediate availability of resources after treatment in the short term and from the mulch itself in the long term (Fornwalt et al. 2017). This finding could be a limiting factor for mulch operations where the species is already rampant.

Brockway et al. (2009) reported a decrease in understorey tree seedlings and an increase in shrubs, vines, and grasses 13 months after their mulching treatments in loblolly pine stands. After two years since mulching and one year since a prescribed fire, the foliar cover of all vascular plants doubled, which was attributed to the recovery of trees at the sites. Where prescribed fire occurred in winter and spring, shrub and vine cover were significantly higher than in controls. Species richness decreased in mid- and overstorey trees after mulching treatments but increased in understorey plants. The stand structure changed where mulching converted the midstorey trees into chips, resulting in a more open stand of longleaf and loblolly pine (Brockway et al. 2009). Ladder fuels were also reduced, leading the authors to conclude that mulching has potential as a wildfire reduction tool in stands with frequent surface fire disturbance. However, the influx of sprouting after mulching requires that prescribed fire be used frequently after mulching to maintain a reduced density (Brockway et al. 2009). The authors suggested that prescribed fire be applied to mulched sites within 18 months of treatment to remove hardwood sprouts, which supports the frequent surface fire regime that longleaf pines need.

Fernández and Vega (2016) found no increase in invasive species after their mulch treatment of post-burned and salvage-logged sites. This study used *Eucalyptus globulus* mulch produced at a timber processing plant that was then brought to the site. The focus of this study was on how mulch could be used in erosion control. Interestingly, the authors found that seedling height was affected by the treatments, in that taller seedlings occurred in sites where no mulch and no salvage logging took place.

Morgan et al. (2014) studied mulching on post-burned soils and the response of native vegetation several years later. They found that mulching and seeding influenced cover and diversity for up to six years after a fire and helped reduce soil erosion on steep slopes (50–70% slope). More specifically, using hydromulch, which contains wood fibre, tackifier, and local grass seed, resulted in more species diversity than wood mulch alone, which Morgan et al. (2014) theorized could be due to the mulch acting as a barrier for plant re-establishment. Interestingly, the authors noted an increase in shrubs over the six years, but an increase and then decrease in grass and forbs during the same period, except in the hydromulch and seeding treatments, suggesting that mulching with wood or straw reduced grass cover in the years after the treatment (Morgan et al. 2014). They recommend a longer time frame for vegetation monitoring to better understand how species respond to treatments.

Wolk et al. (2020) compiled existing data on mulched (masticated and chipped) fuelbeds in Colorado into a report to define the benefits and limitations of the technique, including the effects of mulching on plants. If mulch depth is too deep (exceeding about 3 inches, or 7.5 cm), it can negatively impact plant growth, and at a depth greater than 6 inches (15 cm), it can prevent all understorey plant growth. In mulched mixed conifer sites in Colorado, the median mulch depth ranged from 1 to 2.5 inches (2.5 to 6.4 cm), so it is unlikely that these depths are negatively impacting the plants. Similarly, when looking at tree regrowth, the authors suggested that for optimal establishment of tree seedlings, mulch depth should not exceed 2 inches (5.0 cm). Three to five years after treatment, understorey plant abundance in mulched fuelbeds was similar to or greater than that in untreated areas. Understorey plants that spread vegetatively were more abundant than plants that spread via seed dispersal. Areas with mechanical forest treatments in general (not just mastication and chipping) and disturbance from wildfires exhibited an increase in invasive plant species. However, there was no evidence that mechanical treatments caused the increase; areas with a high diversity of native plants also had high instances of invasive plants. Six to nine years after mulching, establishment and regeneration of tree seedlings were the same or greater in mulched sites as in untreated sites, which suggests that dedicated reforestation activities are not needed after a mulching treatment. Resprouting bushes varied in their response to mulching; some sites reached a pre-treatment density within one year, while others did not recover after the treatment, suggesting that more studies are needed on this topic.

Jain et al. (2012) reviewed fuel management practices in northwestern US. Depending on the forest structure and composition of a stand after treatment, a fuel treatment might not improve forest health unless it is well planned. In some cases, maintaining forest health may require a mosaic of different fuel treatments to ensure different successional stages and plant community structures.

Mastication

Mastication can reduce herbaceous regrowth by limiting light and seed access to soil and by influencing soil temperature, as was reported by Evans et al. (2011) in a literature review of fuel treatments in mixed conifer stands. Jain et al. (2018) provided an overview of other studies that monitored vegetation response to mastication and summarized that some considerations that should be made include monitoring length (time since treatment), site vulnerability to invasive species, residual tree mortality, and additional treatment planning (such as prescribed fire), all of which have variable influences on vegetation.

Brennan and Keeley (2017) studied vegetation response to mastication treatments in chaparral shrublands and compared it to that at burned sites. Though masticated sites had less live cover, they had more species richness and density overall. Shrub cover and density were reduced in masticated sites, but the incidence of herbaceous and suffrutescent species doubled (Brennan and Keeley 2017). Invasive species were more abundant in masticated sites, but native species remained dominant, with a ratio of 10:1. Brennan and Keeley (2017) made the interesting observation that obligate seeders did not resprout after mastication, whereas facultative species were common after treatments. Eight years after mastication, the authors found that shrub cover and height had approached similar levels to those in untreated stands, with small woody plants remaining twice as abundant.

Kobziar et al. (2013) noted a rapid regrowth of shrubs after their mastication treatments in plantations, recently burned sites, and mature pine stands. In the plantations, the total fuel loading had increased within 16 months after treatment due to the shrub regrowth and 1000-h fuels. In mature pine flatwood cites overstories were not influenced by treatments; changes to tree density, basal area, and diameter occurred only after the sites were burned. Shrub density was the only factor that changed with mastication treatments, but Kobziar et al. (2013) noted more shrub recovery in the mastication only sites before performing a prescribed fire six months later. Species richness (shrubs and trees) was lower only in burned sites but recovered within a year.

Little et al. (2019) found that mastication in a white spruce and mixed hardwood area led to changes in understorey vegetation composition, namely, an increase of fireweed (*Chamerion angustifolium*), and a decrease of ferns, shrubs, and grasses. Graham et al. (2004) warned that when masticated fuels decompose, the organisms responsible for this process use large amounts of nitrogen, limiting its availability to plants.

Pickering et al. (2022) studied masticated fuelbeds at 53 sites in Australia that included dry forests, lowland forests, woodlands, heathlands, and coastal scrub grasslands to examine changes over time. The mean plant height increased by approximately 0.2 m per year after mastication. Plants <50 cm tall regrew faster than those in the other size categories, covering 40% of the masticated beds after two years and 85% of the beds after four years. The cover of standing fuel increased in the first four years after mastication, to a maximum of 40%, then decreased with time. After nine years, the percent cover in masticated sites was still 0–15% less than in untreated sites, and plants ranging from 60–100 cm in height in the masticated areas had half the percent cover of those in the untreated areas. Plants taller than 100 cm made up 15% of the cover in masticated sites (25% of the percent cover in untreated areas).

Reed (2015) wrote a master's thesis on the decomposition of masticated fuels and the regeneration of woody plants and trees in those fuels over time in northern California and southern Oregon. Reed found that total fuel load decreased by an average of 20% throughout the eight- to nine-year sampling period, but that the 1- and 10-h fuels decreased on average by 69% and 33%, respectively (2015). As fuels decomposed, woody vegetation recovered. Reed's results showed that woody vegetation height increased by an average of 8.1 cm a year (2015). Of the shrubs and trees that regenerated in masticated sites, resprouting hardwood shrubs and trees generally gained height more rapidly than non-sprouting species, though the magnitude of difference was small. The author suggested that pre-treatment of vegetation contributes to the variability of fuel load immediately after mastication treatments and likely plays a role in fuel load throughout time. Reed (2015) concluded that prescribed fire would likely be a useful treatment where it is possible, as it reduces surface fuels faster and increases fuel treatment efficacy. Morgan et al. (2018a) noted that fire response shrubs, such as nine bark (*Physocarpus opulifolius*) and ocean spray (*Holodiscus discolor*), and other understorey species retuned quickly after masticated beds were burned.

Young et al. (2013) studied how mastication of encroaching Utah juniper (*Juniperus osteosperma*) woodlands may impact plant establishment in western Utah, USA. After mastication, bluebunch wheatgrass (*Pseudoroegneria spicata*) and cheatgrass were seeded by hand in fall before field measurements were taken. The authors found that fewer seedlings of both species emerged in the masticated areas than in the untreated areas, likely due to increased cover from masticated juniper debris. The authors noted that cover can increase emergence by reducing evaporative water loss, but that at a certain point, thick cover can physically impede seedling emergence while blocking light and precipitation. Their study confirmed that seedling emergence gradually declines with increased cover of juniper debris, and that spreading masticated debris thinly across the masticated sites would increase establishment of the grass species studied. However, the seedlings that did emerge in the masticated areas had more aboveground biomass than in the untreated areas, likely due to greater soil inorganic nitrogen, more wet days, and warmer soil temperature in masticated areas. In practice, the authors recommend that if mastication is done with the goal of restoring native grasslands, the desired native perennial grass species should be planted after mastication, especially if the area may have lost those species due to many years of encroachment by other species. Dominant invasive annuals such as cheatgrass may need to be controlled with selective herbicides to allow the slower-growing perennial grasses to become established. In this study, reducing soil inorganic nitrogen alone during the seedling phase did not enable bluebunch wheatgrass to outcompete cheatgrass. It is possible that water was the more important limiting factor for seedling establishment in this ecosystem, as water is required for soil nutrients to diffuse. Limiting soil nutrient availability will help mature perennial grasses that have nutrient-conserving structures compete with invasive annuals.

Carvajal-Acosta et al. (2015) studied the impact of mastication treatments on short-term vegetation response in ponderosa pine forests of southern Nevada, specifically in the context of plant habitat for the rare endemic Mount Charleston blue butterfly (*Plebejus shasta charlestonenesis*). The authors established 14 plots, two of which were untreated controls and the remaining 12 were treated by mastication. The 12 treated plots had four quadrats. One quadrat was bare after all wood chips and litter had been removed, the second had a wood chip depth of 2.5 cm after wood chip removal, the third had a wood chip depth of 5 cm after removal, and the final was left undisturbed, with the original wood chip layer. The average depth of wood chips was 5 cm across all plots. Plant response was measured at all plots one month after the mastication treatment and then three months after the treatment. The authors found no significant effects on species richness or plant density over time, but the percent cover of understorey plants decreased from the time of the first measurement to the second (though not significantly) across the treated plots. In the untreated control plots, plant cover increased by 5%. From this, the authors concluded that the deposition of masticated wood chips did not significantly influence the vegetation components of butterfly habitat or individual plant species, at least in the short term of this study. Carvajal-Acosta et al. (2015) were surprised by this, as they had hypothesized that a 5 cm wood chip depth would have an inhibitory effect on the growth and survival of buried plants. They speculated that it was possible that the lack of fire used in the treatment may have contributed to the limited understorey vegetation response.

Sikes and Muir (2009) compared the impacts of mastication to those of hand-thin, pile, and burning (HPB) in a southwest Oregon chapparal plant community, with a special focus on buckbrush (*Ceanothus cuneatus*). In both treatments, the authors reduced shrub cover by approximately 75%. Shrubs were removed from directly under trees or within a 3 m radius, and shrubs in the open were thinned to clumps and spaced apart from one another. Plots were measured one year and two years after the treatments. The authors were surprised by the relatively small impacts on the herbaceous plant communities considering the dramatic reduction in shrub cover. They estimated that the lack of overall mastication effects may be due to the general increase in species abundance that occurred in the first year being counterbalanced by a decrease by the second year. The initial increase may have been caused by the immediate increase in resources and disturbance. Notably, the mastication fuel treatment resulted in buckbrush regeneration even in the absence of fire, meaning that the reduction of standing fuels would be short lived. This increase in buckbrush may be because mastication scarified the seeds, allowing them to germinate. This may have had a positive effect in discouraging exotic species presence and abundance after treatment, but it may have defeated the purpose of the fuel treatment as a measure for reducing fire risk. Native weeds decreased in mastication treatment plots, as did species diversity. The authors noted that their results did not align with that of other research on mastication fuel treatments in similar nearby ecosystems, where exotic annual grasses were twice as abundant on masticated and HPB-treated sites compared to controls four to seven years after treatment. The authors stated that they expected to see greater dominance in species composition of weedy plants, which specialize in colonizing new and disturbed habitats after a treatment. Instead, these species were not significantly more abundant in the first year than in the second, and the change in their percent cover was not large compared to that for other plants.

Munson et al. (2020) evaluated the cost-effectiveness of widely removing woody plants and herbaceous invasive plants and conducting seeding treatments for restoring drylands in Utah, USA. Mastication and aerial seeding were the most effective treatment in reducing woody plant cover, though the costs were three times greater for removing woody plants by mastication than by chaining or harrowing. The authors noted that mastication has higher costs per area because it selectively removes individual woody plants, whereas the other treatments remove plants indiscriminately. This is partly why the use of mastication is increasing relative to chaining and harrowing. Woody plant cover decreased as the cost of vegetation removal increased across all treatment types, but mastication was the only treatment that significantly reduced woody plant cover with increasing treatment costs. All mechanical treatments, including mastication, increased cheatgrass cover, implying that there is a negative effect associated with removing vegetation and disturbing soils using heavy machinery. Spending more on mastication and aerial seeding had no effect on decreasing cheatgrass cover. Throughout time, woody plant cover increased by 0.7% per year for every treatment. The authors expected that mastication would have been more effective than the other treatments at discouraging woody plant recovery. However, there is some evidence that spending more on removing woody plants by mastication led to a prolonged reduction in woody plants. Cheatgrass cover did not change significantly throughout time at all treatments. In contrast, seeded perennial grass cover increased by 0.3% per year across all treatment types. Notably, seeded perennial grass cover increased with mean annual precipitation at mastication and aerial seeding treatment areas. The limited increase in perennial grass cover after mastication and aerial seeding relative to the treatment costs in this study disagrees with the results from Young et al. (2013), who reported that mastication and seeding treatments increased herbaceous cover by up to three times relative to the control. Munson et al. (2020) hypothesized that the reason for this is because their study area was wetter than that in Young et al. (2013), or because woody debris and leftover herbaceous layers inhibited the establishment of grasses and forbs. Regarding the impact of seed composition on ground cover, the authors stated that this study provides no evidence that seed mixes with a greater native species composition led to a greater increase in ground cover. A high composition of native species in seeds mixes led to a short-term increase in species richness, but this did not persist beyond the initial two or three years after treatment. Alternatively, the non-native species used in the seed mixes resulted in a large increase in ground cover after treatment. The high growth potential and other advantages of non-native species explain why they are used for restoration projects, though their long-term persistence and the population growth of introduced species can lead to low establishment of native species and the associated diversity throughout time. Across all treatments, wetter years benefited seeded species but also promoted high cheatgrass cover, which can increase competition for soil water. This factor led Munson et al. (2020) to recommend that land managers consider weather and other environmental factors when deciding how to use limited funding on restoration or rehabilitation treatments.

In Potts et al. (2010), the authors compared the effects of prescribed fire to those of mastication for three years after treatment, focusing on shrub cover, height, seedling density, and species composition, in a northern California chaparral ecosystem. Large mammal herbivory effects after treatment were also monitored. Mastication treatments had an average of only 43% shrub cover three years after treatment (relative to >90% before treatment). This was lower than the shrub cover after prescribed fire, likely because masticated sites release nutrients more slowly as shredded biomass decays, which causes slower regrowth. However, the results from this study and others in Mediterranean shrublands suggest that these ecosystems are highly resilient to disturbance, whether it be through fire or mechanical treatment. Seedling density was lower after mastication, which was expected due to the number of fire-adapted species whose seeds need fire to be released from dormancy. Despite this, fire-adapted species resprouted in mastication sites, perhaps because the high solar heating of the residual shrublands triggered a release from dormancy. Seedlings experienced greater mortality in spring mastication than in fall mastication. This is likely because germinating plants have insufficient time and resources to establish roots that can withstand the heat of the oncoming summer months. Chamise (*Adenostoma fasciculatum*), a more flammable shrub, was the more dominant shrub in all sites before treatment and remained so afterwards. By the third year, fall mastication treatments showed seedling recruitment for both chamise and buckbrush, the latter of which has high nutritional value for wildlife, despite the absence of fire. Deer herbivory most affected shrub height in the third year after mastication treatments.

This may be due to the ease of movement deer have through areas that were masticated versus areas that were burned, and this would increase access to more resprouting shrubs. The authors concluded this publication by stating that mastication treatments are likely better than prescribed fire for longevity of treatments, due to a slower shrub regeneration rate, but that the fine fuel addition from mastication may increase fire hazard. Refer to Potts et al. (2010) for citations of each example mentioned.

Kane et al. (2010) compared the effects of different fuel treatments on the response of understorey vegetation in a second-growth ponderosa pine forest in the northern Sierra Nevada of California. The treatments compared were mastication only, hand removal only, mastication paired with tilling, mastication paired with prescribed fire, and a control. Every treatment resulted in greater plant cover relative to the control, suggesting that understorey vegetation responded to the release from shading, increase in growing space, and/or decrease in competition. The understorey was dominated by resprouting perennial shrubs. Plant recovery at the study sites may have been slower if the sites mainly consisted of species that germinate from seed. The small plot size and resulting increased edge effect may have also contributed to the increased plant recovery rates observed. While the midstorey was substantially reduced in all treatments, treatments did not result in a substantial decrease in canopy closure because overstorey conifers were retained. Across all treatments, the proportion of bare ground was positively correlated with understorey species diversity indices as more bare ground may allow for greater recruitment and establishment of individual plant species. The mastication and tilling treatment and the mastication and prescribed fire treatment directly increased the amount of bare ground. In contrast, the mastication only and hand removal only treatments maintained or decreased bare ground cover relative to the control. The greater amount of exposed and disturbed mineral soil promoted the germination of the shrub seed bank through scarification or chemical cues in the mastication treatments paired with tilling or prescribed fire. Conversely, litter cover and depth were negatively correlated with species richness. The control, and the hand removal only and mastication only treatments also resulted in greater litter cover and depth. However, the additional organic material that was deposited on the forest floor following mastication did not reduce species richness, as the control and the hand removal only treatment did. The physical barriers caused by organic materials may have been offset by soil disturbance that was caused indirectly by the mastication equipment, which stimulated plant recovery. The shift in understorey plant composition in the treatments was associated with more bare ground, less litter cover, and lower canopy closure. The mastication only and hand removal only treatments dramatically reduced midstorey vegetation but had little impact on understorey richness, compared to the control, without the subsequent consumption of the forest floor through prescribed fire. The mastication and prescribed fire treatment increased native species richness by 150% compared to the control, but it also increased non-native species richness and shrub seedling density. Mastication and tilling increased non-native forb density. The authors expressed great concern about fuel treatments increasing non-native plant species. Because the mastication and prescribed fire treatments were measured only one year after the treatment was complete, it is possible that non-native plant cover may rise in these treatment areas in the future. Research is needed on the long-term persistence of non-native species after fuel treatments.

Morgan et al. (2018a) reported that no tree mortality occurred in ponderosa pine stands in which masticated fuels were burned. However, the authors reported that some trees were injured during the mastication process, but recovery was quick (Morgan et al. 2018a).

Prescribed Fire

In a study by Brennan and Keeley (2017), masticated treatments in chaparral ecosystems were compared to similar sites that had been burned by wildfire. The authors noted that the biggest structural difference was the lack of ground cover by woody debris found at post-fire sites compared to masticated sites. More post-fire endemic plants occurred on burned sites that did not exist on masticated sites, despite their proximity and similar site characteristics. Masticated sites were found to have 22 more species, on average, than burned sites, but cover and density were not statistically different until after two years, when plant cover increased by 25% in masticated sites, and density in masticated sites was five times greater than in burned sites (Brennan and Keeley 2017). These structural differences were attributed less to the treatments and more to the severity of the wildfire, which caused more damage to the vegetation than mastication treatments, potentially hindering re-establishment more than a prescribed fire would. At a regional scale, burned sites had significantly more native species cover, density, and richness, with invasive species noted in both treatments. However, this was attributed to masticated sites having lower shrub density overall compared to pre-wildfire sites, and to lower recruitment of obligate seeding species that rely on fire for germination (Brennan and Keeley 2017). The authors concluded that masticated sites could emulate post-fire communities in the first two years after disturbance, but they will have a different structure and a denser ground cover of woody debris. In the long term, mastication is not an exact replica of fire disturbance in chaparral systems as ephemeral species require fire for germination (Brennan and Keeley 2017), and mechanical treatments do not meet this criteria.

In a single-replicate under-burning study by Baxter and Ault (2013), vegetation recovery was minimal in the treated plots having a density of six jack pine seedings under 13 cm in height on average eight years after treatment. The control plots showed no recovery after the same eight-year period.

Chiono et al. (2012) found no clear trends in tree or shrub recovery after pruning treatments either on their own or followed by prescribed fire or pile burning in California. This may have been due to variability in site conditions. However, alterations to forest structure, including reduced continuity of vertical and horizontal fuels and increased prevalence of large trees, were evident even 15 years after treatment.

Kalies and Kent (2016) reviewed 56 studies that focused on wildfires along the west coast of the US in which treatments in the burned area included thinning, prescribed burning, or thinning and burning. When looking at regrowth after a wildfire, the authors found that tree seedlings were more abundant in treated areas compared to a control. Another study found that ponderosa pine regrowth was patchy, but young trees were denser in the treated areas. Eight years after a wildfire, thinned and burned sites had greater pine regeneration than the control. However, the effects of treatment on understorey vegetation were extremely variable from study to study; no trends could be identified. In some studies, treatment improved plant regrowth and diversity after a fire, and in other studies plant response was better in the control sites.

Jain et al. (2012) reviewed fuel management practices in northwestern US, including prescribed fire practices that help to protect plant life. Backing fires, or fires started along a baseline such as a road or stream and made to burn into the wind or downhill, are commonly used because there is little heat transferred to the overstorey canopy, which can protect the upper parts of trees. However, backing fires can damage roots if the duff layer does not have enough moisture (at least 20% moisture is suggested). Actively growing plants might be more susceptible to fire damage, and burning may cause the plants to use stored carbohydrates to repair damage. Some studies suggest burning outside the growing season, while others say that a low intensity burn in any season is better than a higher-intensity burn outside the growing season (original sources cited in text on page 164 of Jain et al. [2012]). Burning high accumulations of litter and duff can lead to delayed mortality of large-diameter trees three to five years after the prescribed fire, potentially since smouldering duff mounds can exceed 400°C for over 16 hours. Thus, duff should be removed from a minimum of 9 inches around the base of the tree using a rake or a leaf blower if there are no roots visible. If there are roots, ensure that the duff above does not smoulder long enough to damage them, or conduct the burn in a season when the roots are least active.

The California Department of Forestry and Fire Protection wrote a Fuels Reduction Guide (CAL FIRE n.d.). Prescribed fire in ecosystems that are adapted to fire can eliminate invasive plants.

4.b. Attraction of Insects

Chipping

Fettig et al. (2006) explicitly studied the impact of chipping operations on bark beetle attacks in ponderosa pine forests in Arizona and California, USA. The study consisted of seven possible treatments of sub- and unmerchantable trees in Ponderosa pine forests: (1) chipping in spring, (2) chipping in late summer, (3) chipping and raking in spring, (4) chipping and raking in late summer, (5) lop and scatter in spring, (6) lop and scatter in late summer, and (7) an untreated control. In the ponderosa pine stands in their study area, the authors found evidence that bark beetle attacks on residual trees are exacerbated by the chipping of sub- and unmerchantable trees and other logging residues. They observed a threefold increase in the proportion of residual trees attacked in treatments 1 and 3 (chipping in spring, and chipping and raking in spring) versus treatments 5 and 6 (lop and scatter in spring, and lop and scatter in fall). Bark beetles are attracted to the monoterpene odours emitted by the chipped material. The most common bark beetle that attacked residual trees was red turpentine beetle (*Dendroctonus valens*), but the percentage of western pine beetle (*Dendroctonus brevicomis*) was significantly higher in plots that were chipped in spring compared to the untreated control plots. A key component of these results relates to the time of year in which the chipping was done. Spring chipping plots had higher bark beetle attacks on residual trees, likely because many bark beetle species are in peak flight during spring. Raking the chips away from the boles of residual trees may reduce the source of strong monoterpene odours and therefore draw away insects. However, the benefits of raking could be offset by damage to fine root systems, which could result in greater monoterpene odours emitted, or may weaken the trees, making them more susceptible to other biotic agents, such as root weevils and pathogens. No significant differences in the amount of tree mortality caused by bark beetle were observed among treatments, and the mean mortality rate ranged from 0.9% (untreated control) to 3.1% (chipping in spring). Most mortalities were attributed to either *Ips* or *Dendroctonus* species. These estimates may be low; the authors recommended more future monitoring of post-treatment effects. The authors also cautioned that their estimates for tree mortality were confined to plot boundaries and the impacts chips have on attracting bark beetles may influence a larger area. Chapter 7 of this literature review contains a series of recommendations produced by these authors to reduce the likelihood of attracting bark beetles after chipping treatment.

Prescribed Fire

The intensity of insect infestations following fire depend on the insect populations during and after treatments, as was noted in a literature review by Evans et al. (2011). Most beetle kill occurs two years after fire and can be facilitated where slash is piled and left near residual trees (Evans et al. 2011). Kalies and Kent (2016) reviewed 56 studies that focused on wildfires along the west coast of the US in which treatments in the burned area included thinning, prescribed burning, or thinning and burning. Trees in the thin and burn treatment areas were less likely to be attacked by bark beetles after a wildfire.

Jain et al. (2012) compiled a review of fuel management practices in the northwestern US. Prescribed fire can make trees more vulnerable to insect attack. For example, western pine beetles attack stressed trees. The authors warned that starting a regime of prescribed fire in areas with a long history of fire suppression can make trees vulnerable to the beetles. Meanwhile, pine engraver (*Ips spp.*), Douglas-fir (*Dendroctonus pseudotsugae*) and fir engraver beetles (*Scolytus ventralis*) kill trees that were scorched by low intensity fires, making this a concern for prescribed burns.

Raking
Nesmith et al. (2010) found that raking surface fuels away from residual trees significantly reduced beetle populations after prescribed fire compared to unraked areas.

4.c. Soil Disturbance

Chipping
Johnson et al. (2014) compared the effects of three treatments (thin + chip, thin + chip + burn, burn only) on soil nutrient profiles. The net carbon and nutrient exports were highest in thin + chip + burn treatments, likely due to the additive effects of treatments and the greater consumption of the native forest floor. This treatment resulted in the loss of 29% of total ecosystem carbon and 13% of total ecosystem nitrogen. When looking at the soil extractable pools, this treatment resulted in the loss of 26% of total phosphorus, 21% of total potassium, 18% of total calcium, 17% of total magnesium, and 30% of total sulfur. By comparison, the thin + chip treatments resulted in the loss of the above-mentioned elements between 1 and 8% of the ecosystem total, while burn only treatments resulted in the loss of 5% of total ecosystem carbon and 4% of total ecosystem nitrogen, and no losses of phosphorus, potassium, calcium, magnesium, or sulfur. Exports of nutrients were greater after harvesting (thin + chip) than burning for calcium, carbon, magnesium, phosphorus, and potassium; approximately equal for nitrogen; and greater after burning for sulfur. The carbon pool in the O horizon increased by 42% using the thin + chip method and by 17% after thin + chip + burn. When comparing chips to the native forest floor, chips were lower in all nutrients other than potassium (chips have three times more potassium than the forest floor). This is likely due to the presence of potassium in chipped foliage, as it is leached out when foliage falls naturally. Potassium levels began to decrease one year after treatment and returned to normal levels at two years. Both burning treatments caused a net decrease in carbon and nitrogen in the O horizon. Thin + chip + burn resulted in net losses of phosphorus, potassium, calcium, magnesium, and sulfur, but there was no change of these elements after burning. Burning treatments resulted in increased ammonium, total mineral nitrogen (nitrate and ammonium), calcium ions, and sulfate for two years after burning. The authors reported that the most significant effect on the ecology was the loss of nitrogen after thin + chip + burn treatments. They noted that repeated prescribed fire could potentially cause long-term nitrogen deficiency; the loss of nitrogen reported would take approximately 200 years to be replenished naturally at the study site. Nitrogen-fixing plants would help to mitigate this but would result in a higher chance of wildfire due to the increased presence of vegetation.

Walker et al. (2012) studied the impact of thinning, chipping, and prescribed fire on understorey shrubs and other plants in mixed conifer forests in the Sierra Nevada. To protect soils on highly sensitive sites, slash generated by chipping was redistributed in a continuous layer over the forest floor.

Kabzems et al. (2011) specifically reviewed the impact of chipping operations on soil productivity in BC and created best management practices for soil conservation. At the time of publishing, the authors reported that there were no specific regulations that addressed organic matter levels on site after biomass harvesting in BC. There are pros and cons to leaving biomass on site. A pro to leaving 10–20% of trees on all biomass harvest sites is that maintaining woody debris can be good for ecosystem processes and biodiversity values. However, the depth of biomass can have a growth-limiting effect. In a chipping example, chip deposits create a physical barrier to plant growth. Kabzems et al. (2011) point to examples in which chips 8–10 cm deep reduced the amount of understorey vegetation in ponderosa pine ecosystems and aspen regeneration in boreal ecosystems for at least three years.

Kabzems et al. (2011) described that surface application of wood chips retains soil moisture by preventing evaporative water loss and reducing soil temperature. This can decrease soil mechanical resistance in spring and summer and can contribute to slower daytime heating. In northeastern BC, soils under 20–30 cm of aspen bark hog fuel had warmer soil temperature at times during the first two growing seasons when compared to soils without a hog fuel deposit, likely due to intense microbial activity. Kabzems et al. (2011) drew on examples that reported that large piles of several hundred tonnes of chips have been known to spontaneously combust under certain combinations of moisture, aeration, and microbial activity.

Kabzems et al. (2011) reported that the nutrient content and chemical properties of chips vary with tree species, the components (bark, wood, or fine branches), and the size and age of the chipped material. Fine materials settle and compact more easily than coarse materials, and in general they decompose more quickly. Fresh wood chips have a high carbon-to-nitrogen ratio and can potentially immobilize 19–38 kg of nitrogen per hectare for the first year after harvesting, depending on the rate of wood chip application and whether the chips are incorporated into the soil. The authors gave examples of nitrogen mobilization from ponderosa pine ecosystems, boreal aspen sites, and lodgepole pine and hybrid spruce ecosystems. However, they also mentioned that chipped woody debris can protect soils from compaction by forestry equipment and can be used in rehabilitation of roads and landings.

Kabzems et al. (2011) specifically reviewed the impacts of chipping mulch on soil and water chemistry. They reported that by increasing soil moisture, chipping treatments can lead to anaerobic conditions by preventing normal gas exchange. This can result in inactivity or death of normal aerobic soil organisms such as those in the root system, decreased forest and forage production, and chemical changes in soil solution and exchangeable ions. Iron, manganese, and other multivalent ions that occur in soils can leach out with subsurface or lateral soil water flow, and when iron is reoxidized by bacteria by being reintroduced to water, water quality is impacted. Kabzems et al. (2011) reported that wood leachate is of particular concern for aquatic ecosystems. Lodgepole pine chips of 10 cm in depth produced high phenols in the first year after application. However, in an example with aspen in a previous study, the phenols produced by aspen slash 4–6 cm deep did not have negative effects on aspen regeneration.

Mulching
Battaglia et al. (2009) reported that soil nitrate and ammonium were not negatively impacted by mulching. Nitrogen availability after mulching differed by forest type, with more nitrogen available in ponderosa pine and mixed conifer forests than in juniper and lodgepole pine forests; the authors attributed this to the depth of the mulch bed. Woody debris in mulched sites resulted in a large increase in nitrogen; this was due to the increased mass accumulating on the forest floor. Mulching promotes microbial growth, which releases carbon (source) and stores nitrogen (sink). This carbon loss due to mulching may continue for many decades and will be higher than at sites that were not treated (Battaglia et al. 2009). The authors reported higher soil temperatures in winter and lower soil temperatures in summer in treated versus untreated sites.

Frame (2011) noted that where mulch depth was 8–15 cm and uniformly applied to a site, soil nitrogen decreased by >50%. The author also mentioned that carbon release persists in treated stands as woody material decays, so although the process is slower, mulched stands will be carbon sources, with potentially fewer trees regenerating to act as future carbon sinks.

In a study conducted three to five years after treatments were carried out by Battaglia et al. (2010), Rhoades et al. (2012) found that nitrogen concentration was lower and carbon higher in mulch particles compared to in untreated O horizons, though these changes persisted for only a year after treatment. Plant-available nitrogen (nitrate) was higher in mulched sites, as was ammonium in the subalpine and montane ecosystems (Rhoades et al. 2012). Additionally, volumetric soil moisture was 1.3 times higher in mulched areas, with subalpine and montane ecosystems showing 48% and 35% more moisture, respectively. These results were most prominent in areas of intermediate moisture content; little influence was recorded where soil moisture was high or low before the treatments (Rhoades et al. 2012). These findings were all influenced by mulch depth, with nitrate being 36% lower under deep mulch in the same year treatments were conducted. After the second year, nitrate levels were similar regardless of mulch depth. Mulch effects on moisture were more evident at lodgepole pine sites in the non-winter months; the amount of soil moisture remained equal to that during spring snowmelt in untreated stands (Rhoades et al. 2012).

Wolk et al. (2020) compiled existing data on mulched (masticated and chipped) fuelbeds in Colorado into a report to define the benefits and limitations of the technique, including the effects of mulching on soil. Soil moisture was higher in mulched sites up to 10 years after treatment, probably because chipped material is incorporated into the soil. Soil carbon dioxide increased for the first few years after mulching, while nitrogen increased in mulched areas, but only after three years after treatment. Fuelbeds with less depth had a smaller impact on soil nitrogen.

Mastication
Kobziar et al. (2013) noted no differences in soil temperature among treatments before prescribed fire but found that temperatures were highest from March to August, ranked in order as follows: mastication + burn, burn only, mastication only, and untreated sites. Sites that that were burned exhibited higher soil temperature into the fall months until December, at which time the burn only sites had lower soil temperature than the other treatments (Kobziar et al. 2013).

Wilkinson et al. (2018) performed two different mastication treatments (mulch thinning and strip mulching) in black spruce stands in Alberta to assess their impact on peat with subsequent prescribed fire. The mulch thinning treatment reduced stand density by felling trees and mulching throughout, whereas the strip mulching involved 5 m wide strips being clear-cut and mulched with 5 m segments of natural forest between. These strips ran perpendicular to the prevailing winds, and prescribed fire was conducted in both treatment sites using helitorch ignition (Wilkinson et al. 2018). The peat burn depth was lower in the thinned sites and peat carbon loss was higher in the stripped areas. The peat bulk density was higher in fuel-treated areas than the controls, and compaction was concentrated to between 5 to 10 cm in depth (Wilkinson et al. 2018). Peat moisture was also significantly higher under masticated fuelbeds, with increased gravimetric water content below 2 cm in depth, particularly in the thinned sites.

Jain et al. (2018) created decision trees to support managers in deciding which equipment to use based on numerous criteria. The third decision tree focuses on soil compaction and recommends certain machinery depending on the soil characteristics (see Decision Tree 3 in Jain et al. 2018).

Cline et al. (2010) studied the hydrologic impacts of mechanical shredding of encroaching juniper trees on sloped grasslands in Utah, USA. In their study, the authors asked whether tire tracking from a heavy shredding vehicle increases soil compaction and whether mulch residue reduces sediment yield and increases water infiltration rate. The authors found that even though tracking from mechanical shredding resulted in some adverse hydrologic effects on grass plots under initially wet soils and heavy rainfall, juniper shredding in their study area had an overall beneficial effect on infiltration and reduction of sediment on sloped grasslands. The authors warned that land managers should still be aware of the factors that promote soil compaction, including high soil water content, heavy loads, repeated passes (often unneeded with shredding treatments), soil disturbance, and the generation of fine sediment. However, mulch residue generated from mechanical shredding increased the infiltration rate and decreased sediment yield on bare soil plots in this study.

In Kobziar (2007), the role of environmental factors and tree injuries in soil carbon respiration after fire and fuels treatments were examined in a mixed ponderosa and Jeffrey pine plantation in the Californian Sierra Nevada. The goal of the study was to answer whether forest floor characteristics, vegetation type coverage, and microclimate were linked to spatial variability in soil respiration, how fire and fuel treatments influenced these relationships, and how fire-induced tree injuries and forest floor consumption were related to soil respiration rate. Five treatment units were established: two control treatments, two mastication + burning treatments, and one burning only treatment. Mastication of small trees (DBH ≤23 cm) and understorey vegetation was used as the fuel treatment and was followed up by prescribed fire a year later. Treatment units were measured multiple times from 2003 (before treatment) to 2005 (after mastication in 2004 and before burning in 2005). Pre-treatment soil respiration was lower where rock and herbaceous species coverage was higher, and higher where trees were closer to the soil plots. Mastication increased the depth of litter and duff in soil plots while reducing shrub and herbaceous plant cover. The contribution of organic matter to soil increases substrate availability for microbial activity and can accelerate the decomposition rate. Despite this, the study did not find that mastication played a significant role in soil respiration, though the deep litter layers did increase soil moisture.

Prescribed Fire

Gray (2011) masticated trees with DBH <20 cm in a mixed-species forest near Cranbrook, BC. The mastication treatment was followed by a prescribed fire, with the goal of consuming the masticated fuels. The author noted that masticated fuels, characterized by a deep layer of compacted woody debris, burns more like ground fuels than surface fuels. The author also warned that this type of fuel smoulders and delivers high temperature to surrounding soils for long periods, which could potentially impact soil structure, chemistry, and biology.

Kalies and Kent (2016) reviewed 56 studies that focused on wildfires along the west coast of the US in which treatments in the burned area included thinning, prescribed burning, or thinning and burning. Studies on soil health in treated versus control areas after a wildfire presented conflicting findings. One study found that treated sites retained nitrogen, while two studies found that soil nutrients declined after prescribed fire, including double the loss of nitrogen in treated sites than in the control site. Another study found that prescribed fire improved the resistance of the soil microbial community and that treated sites exhibited a decreased severity of soil burn. Similarly, 11 studies on carbon retention resulted in split findings: half found that treated areas had lower carbon loss than controls, and the others the opposite. Several found that carbon loss during prescribed fire was greater than the carbon benefits of the reduced fire severity/risk. There was also some evidence that carbon loss/storage depended on the condition of the stand before a wildfire.

The California Department of Forestry and Fire Protection wrote a Fuels Reduction Guide (CAL FIRE n.d.). The guide mentioned that prescribed fire in ecosystems adapted to fire can optimize soil and water productivity but did not provide details on how.

Sikes and Muir (2009) did not study prescribed fire impacts on masticated fuelbeds, but they compared the impact of hand thinning, piling, and burning treatments versus mastication treatments on the plant community in a chapparal ecosystem in southwest Oregon. In their discussion, the authors noted that deep masticated fuelbeds are associated with prolonged soil heating in prescribed fire or wildfire. From this, increased soil damage could come in the form of greater water repellency, altered soil chemistry and structure, seed mortality, and mycorrhizal sterilization.

Kobziar (2007) examined the role of environmental factors and tree injuries in soil carbon respiration after fire and fuels treatments in a mixed ponderosa and Jeffrey pine plantation in the Californian Sierra Nevada. The goal of the study was to answer whether forest floor characteristics, vegetation type coverage, and microclimate were linked to spatial variability in soil respiration, how fire and fuel treatments influenced these relationships, and how fire-induced tree injuries and forest floor consumption were related to soil respiration rate. Five treatment units were established: two control treatments, two mastication and burning treatments, and one burning only treatment. Mastication of small trees (DBH ≤23 cm) and understorey vegetation was used as the fuel treatment and was followed up by prescribed fire a year later. Treatment units were measured multiple times from 2003 (before treatment) to 2005 (after mastication in 2004 and after burning in 2005). Prescribed fire in 2005 significantly reduced the depth of litter and duff in the mastication and burning treatments. In the burn only treatments, litter cover increased, but litter depth decreased relative to the controls. If all other variables were held constant, burning (grouping the burning only treatment and the mastication and burning treatment) reduced soil respiration by 14%. This reduction in soil respiration after fire is supported by other research in forested ecosystems. Soil plots farther away from trees and with greater rock cover had a lower soil respiration rate, while plots with greater bare mineral soil and greater tree coverage were correlated with higher soil respiration rate. Autotrophic (tree-caused) respiration decreased following fire, likely due to damage to the trees. However, heterotrophic respiration likely increased because the new litter from the damaged trees increased the amount of substrate available for decomposition by soil organisms. Therefore, burning lessened soil respiration rate sensitivity to tree proximity and the exposure of bare mineral soil. This study found the prescribed fire was more severe in the burning only unit relative to the mastication and burning unit, as indicated by greater crown damage, basal char, and scorch height. Scorch height in burned stands was negatively correlated with soil respiration, meaning the higher the surface fire intensity, the lower the soil respiration. Most notably, the author's work indicates that aboveground forest features, such as tree proximity or tree injuries, can be used to predict soil respiration (Kobziar [2007]). Refer to Kobizar (2007)) for citations of each example mentioned.

Raking

Brochez and Leverkus (2022) cautioned about the intensive use of mechanical raking in fuel treatments as they noted significant mineral soil exposure throughout their study areas. Their study did not go into detail on soil disturbance beyond visual assessment, but they recommended continued monitoring of species regrowth and crop tree establishment in areas where soils were exposed.

4.d. Windthrow

A study by Schroeder (2006) found that tree species was less important on tree acclimation to windthrow than density or stand structure. The report mentioned no specific fuel reduction methods, but it provided recommendations on how to best reduce wind pressure and windthrow. These recommendations included reducing crown mass, maintaining patches of trees instead of individual trees, creating buffers (Figure 9), and using multi-pass treatments. Schroeder (2006) also provided specifics on how to conduct multi-pass treatments and the appropriate canopy gaps to reduce windthrow.

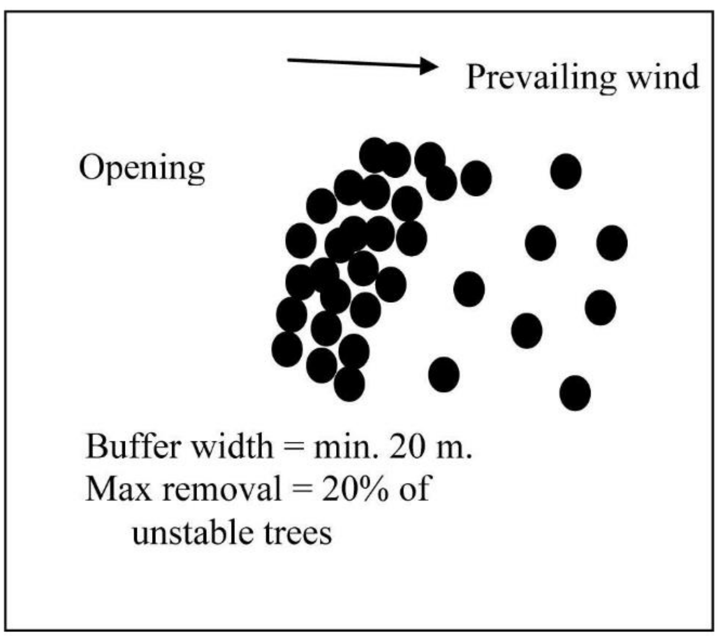


Figure 4. Use of a buffer to protect a treated stand.

Figure 9. Buffer use to protect stands (Figure 4 from Schroeder [2006]).

4.e. Interactions with Wildlife

Jain et al. (2012) reviewed fuel management practices in northwestern US. Any fuel treatment plan should address the potential impact on wildlife (considering space and time) by first studying the wildlife species that use the area and the sensitivity of the habitat to determine how much value the area has for important species. The types of trees should be recorded, along with the cover type, and their density and diameters, and the site should be searched for snags. Snags provide habitat for fungi, mosses, lichens, invertebrates, birds, and mammals. A threshold of snag abundance should be planned and maintained after treatment. As different types and sizes of dead trees are important to different wildlife species, the snags that should be saved will depend on the wildlife species of interest. Similarly, dead or downed wood (1000-h fuels or greater) is important for hiding cover, feeding, habitat, or reproduction for many species. Thought should be given to the habitat patch size and the potential fragmentation and edge effects to determine whether treatment would limit the ability of a given species to disperse for breeding or resources. Fuel treatments should also maintain habitat connectivity to keep corridors of movement for emigration from and immigration to the area.

Chipping

Baxter (n.d.) found an inverse relationship between wildlife suitability and fire behaviour. The three treatments that ranked lowest in wildlife suitability ranked highest in reducing fire behaviour (chip and pile debris, complete removal of debris, and pile and burn).

Mastication

Liu et al. (1996) summarized the guidelines for storing and disposing of wood residue. Wood residue should not be dumped into water as it can smother benthic organisms. Care needs to be taken with the storage and disposal of wood residue, as water moving through the woodpiles (from rain, firefighting water poured on a burning woodpile, or the movement of groundwater) can generate leachate (soluble organic and inorganic compounds). Leachate can run off into nearby streams, which is problematic because some components are directly toxic to fish (e.g., phenolics, resin acids, and tannins). The decomposition of organic matter can also decrease water oxygen levels, and if the leachate is dark in colour, it can reduce light availability in the water and, thus, photosynthesis. Since leachate is acidic, it may release toxic dissolved metals from the surrounding soil and deposit them into waterbodies.

Jain et al. (2012) reviewed fuel management practices in northwestern US. Land protected for endangered or sensitive species can limit fuel treatments temporally (such as during nesting seasons) or spatially (for example, by avoiding dens). Therefore, the needs of wildlife habitat often conflict with the goals of fuel management.

Cook et al. (2017) determined the presence of sage grouse (*Centrocercus urophasianus*) in masticated pinyon pine–juniper areas by conducting pellet surveys and using radiotelemetry. Sage grouse were detected in 56.3% of all treatment plots, but the probability of use was not found to be different when treated and control sites were compared (Cook et al. 2017). The age of the treatment also influenced sage grouse detectability, in that the species was more detectable in older stands (Cook et al. 2017).

Knick et al. (2014) evaluated the sagebrush bird community response to mastication of encroaching pinyon pine and juniper. One site showed an increase in sagebrush sparrows (*Artemisiospiza nevadensis*), while the others exhibited no differences between pre- and posttreatment survey periods (Knick et al. 2014).

Generally, the impacts on soil, plants, and wildlife should be carefully considered if mastication is used. Treatment plans must also should be based on a thorough site evaluation, including examining slope, risk of exotic species invasion, soil vulnerability to erosion or compaction, and treatment costs (Jain et al. 2018).

Pile Burning

The California Department of Forestry and Fire Protection wrote a Fuels Reduction Guide (CAL FIRE n.d.). The guide mentioned that prescribed fire in ecosystems adapted to fire can improve habitat for wildlife but did not provide details on how.

5. Cultural and Non-timber Interactions

In their review of the literature Wynecoop et al. (2019) found few studies have been conducted on fire management in Indigenous communities, or on the interaction of fuel treatments with cultural values. Though their study focused on prescribed fire and mechanical thinning, the authors explored several points that may be applied to chipping, mulching, or mastication. Indigenous participants in the study stated that removing slash from thinning treatment (potentially by chipping) was important for protecting culturally significant plants in the case of wildfire, while also allowing easier access to food, medicines, and firewood. Participants were concerned about the impact that wildfire and mechanical thinning would have on culturally important plants, many of which could be easily damaged or destroyed by mulching. The study also found that fire (whether prescribed fire or wildfire) increased understorey species richness and diversity in their area (Wynecoop et al. 2019). The authors concluded that mechanical treatment would need to be supplemented by a strategic use of fire to encourage plant diversity in a treated area.

More research is needed to better understand the ecocultural interactions with fuel management methods, including mastication, chipping, and mulching.

6. Comparison of Treatments

Mulching

Wolk et al. (2020) compiled existing data on mulched (masticated and chipped) fuelbeds in Colorado into a report to define the benefits and limitations of the technique, and included recommendations for management decisions. They suggested that plans to mulch an area should include the percentage of the management area that will be covered in mulched material, the maximum allowable mulch depth (to limit the effects on plants), the maximum mulch patch size, the maximum size of mulched pieces (diameter and length), and the average mulch depth. The authors also compared mastication and chipping. They found that chipping results in greater control over mulch depth and distribution, lower equipment costs, minimal physical soil disturbance, and the possibility of using the biomass produced if the chipped material is removed from the site. On the other hand, equipment used in mastication is easier to operate in difficult terrain, takes less time than chipping, has lower labour costs, and results in less compaction of the fuelbed than chipping does, allowing for increased herbaceous plant recovery. Chipping and mastication should be combined with other vegetation management strategies, and neither chipping nor mastication should be carried out within 30.5 m of a structure due to the increased combustion and long smouldering time in fuelbeds that could complicate fire suppression if they caught on fire.

Hvenegaard (2020) suggested that fine mulching would not be possible in areas with a thick duff layer and rocky soil, as the high amount of mixing of the duff and soil layers could damage equipment and potentially roots. Site conditions also play a role in deciding which mulch size is practical. Mulching in boreal black spruce forests is conducted during the winter as frozen ground allows entrance to areas with a high water table, and coarse mulching is easier to carry out if there is a lot of snow cover. Hvenegaard (2020) concluded that fine mulching should be used if it will be the only treatment for fire reduction. However, if mulched material will be burned, coarse mulching is more cost-effective because it requires fewer passes with machinery and burns more easily.

The California Department of Forestry and Fire Protection wrote a Fuels Reduction Guide (CAL FIRE n.d.). Their fuel management teams included foresters, environmental scientists, hydrologists, soil scientists, archaeologists, biologists, and fire personnel.

Mastication

Jain et al. (2012) reviewed fuel management practices in northwestern US. If an objective of a fuel treatment plan is to masticate fuels to encourage the decomposition of the mulched wood left behind, there are many factors to consider when planning the treatment. The site should be studied to determine the soil temperature (the ideal temperature for decomposers ranges from 15 to 30°C), site moisture (the ideal moisture for decomposers varies from 30 to 240%), oxygen availability, substrate quality, and presence of decomposing organisms. Planning should include the substrate/piece size of the masticated material. If the material is too fine, the pieces might dry quickly, insulating the ground and not promoting decomposition. Small pieces are more likely to be dispersed when burned, causing a higher chance of igniting other fires outside the masticated area. Pieces larger than 3 inches may be most desirable. Planners should also be aware of the proportion of bark, sapwood, and heartwood that will be in the masticated material, as heartwood takes longer to decay than sapwood. It is important to know which plant species will be masticated. Shrubs decay more quickly than conifers and true firs decay more quickly than Douglas-fir, western larch (*Larix occidentalis*), and western redcedar (*Thuja plicata*). If mastication equipment travels on top of masticated materials without repeating its path, there will be minimal soil compaction. To improve habitat for wildlife, mastication treatments should avoid creating a homogenous bed of material; rather, some areas should be left without masticated material, and the use of other treatments should be considered to isolate masticated beds from one another. The layer of mulched wood left behind after mastication prevents soil erosion from rain or snowmelt. Mastication may be a viable option if the area cannot support burning, if removing excess fuels is too expensive, or if there are concerns about soil and sedimentation.

Sikes and Muir (2009) compared the impacts of mastication to those of hand thinning, pile, and burn (HPB) treatment in a southwest Oregon chapparal plant community, with a special focus on buckbrush. In both treatments, the authors reduced shrub cover by approximately 75%. Shrubs were removed from directly under trees or within a 3 m radius, and shrubs in the open were thinned to clumps and spaced apart from one another. Plots were measured one year and two years after treatment. The authors were surprised by the relatively small impacts on the herbaceous plant communities considering the dramatic reduction in shrub cover. They were also surprised to see few differences in plant community response between the treatment types, as there were great differences in soil disturbance and in the quantity and distribution of woody material between the treatment types. Despite this, treatment impacts were slightly greater in the HPB treatments than in the mastication treatments, and were more pronounced in the first sampling year than in the second. Both fuel treatments encouraged the regeneration of buckbrush even in the absence of fire, meaning that the reduction of standing fuels will likely be short lived. This could have positive impacts, in that the presence and abundance of exotic species would be reduced after treatment, but it likely defeats the purpose of a fuel treatment. The mastication treatment reduced buckbrush more than the HPB treatment did, but this difference is due to the greater regeneration of buckbrush in the pile-burned circles at HPB plots, as buckbrush has an affinity for burned areas. The authors noted that burned areas were not the only areas of buckbrush regeneration. The mastication plots exhibited higher buckbrush regeneration than the control plots, perhaps because the treatment scarified the seeds and improved the microhabitat. Relative to the control plots, native weeds increased by 26% in the HPB plots, while native weeds slightly decreased in the mastication plots. The authors explained this by pointing to the treatment-specific differences in the distribution of woody debris between the treatment types. While HPB treatment may have led to an increase in weedy or non-native species, the treatment also increased native plant diversity by promoting species with fire-cued germination.

In contrast, to the HPB treatments above, mastication treatment plots experienced a decrease in plant diversity. Species abundance also decreased in the mastication treatments relative to the control plots, whereas in HPB treatments, species abundance decreased from year 1 to year 2 of sampling but was still higher than in the control plots. The increases in species abundance for the treated plots versus the control plots in the first year were likely due to an initial pulse of resource availability and fresh site disturbance. The authors expected that weedy plants that specialize in colonizing new and disturbed habitats would dominate the species composition after treatment, but they were not significantly more abundant in the first year than in the second, and the percent change in composition was not large compared to that for other plants. The authors noted that their results did not align with those from other research in a similar ecosystem nearby, where exotic annual grasses were twice as abundant on HPB- or mastication-treated sites compared to controls four to seven years after treatment. The results of this study did not support the hypotheses presented by Sikes and Muir (2009). The results suggest that neither fuel treatment is a definite detriment to the plant community over the one- to two-year period after treatment. The authors suggested this may be due to the history of disturbance and the already extensive occurrence of introduced species at the study site.

Munson et al. (2020) evaluated the cost-effectiveness of widely removing woody plants and herbaceous invasive plants and conducting seeding treatments for restoring drylands in Utah, USA. Four treatments were compared, including aerial herbicide (Imazapic) and drill seeding, harrowing and broadcast seeding, chaining and aerial seeding, and mastication and aerial seeding. Mastication and aerial seeding was the most effective treatment at reducing woody plant cover, though the costs were three times greater for removing woody plants by mastication than by chaining or harrowing treatments. The authors noted that mastication has higher costs per area because it selectively removes individual woody plants, whereas other treatments remove plants indiscriminately. This is partly why the use of mastication is increasing relative to chaining and harrowing treatments. Woody plant cover decreased as vegetation removal cost increased across all treatment types, but mastication was the only treatment that significantly reduced woody plant cover with increasing treatment costs. For impacts on invasive plants, the herbicide and drill seeding treatment was the only treatment that reduced cheatgrass cover. All the mechanical treatments increased cheatgrass cover, implying that there is a negative effect associated with removing vegetation and disturbing soils using heavy machinery. Throughout time, woody plant cover increased by 0.7% per year for every treatment. The authors expected that mastication would be more effective than other treatments at discouraging woody plant recovery. However, there is some evidence that spending more on removing woody plants by mastication led to a prolonged reduction in woody plants. Cheatgrass cover did not change significantly throughout time for all treatments. In contrast, seeded perennial grass cover increased by 0.3% per year across all treatment types, except for the chaining and aerial seeding treatment, in which they increased by 0.5% per year. Notably, seeded perennial grass cover increased with mean annual precipitation in the herbicide and drill seeding and the mastication and aerial seeding treatment areas. The limited increase in perennial grass cover after mastication and aerial seeding relative to the treatment costs in this study disagrees with the results from Young et al. (2013), who reported that mastication and seeding treatments increased herbaceous cover by up to three times relative to the control. Munson et al. (2020) hypothesized that the reason for this is because their study area was wetter than that in Young et al. (2013), or because woody debris and leftover herbaceous layers inhibited the establishment grasses and forbs. Across all treatments, wetter years benefited seeded species but also promoted high cheatgrass cover, which can increase competition for soil water. This factor led Munson et al. (2020) to recommend that land managers consider weather and other environmental factors when deciding how to use limited funding on restoration or rehabilitation treatments.

Stephens et al. (2012) reported on the impacts of fuel treatments on fuel load and potential fire severity in five study areas throughout western US. The forests studied were either ponderosa pine dominated or mixed conifer. Fuel data was collected and modelled using FMAPlus to assess fire behaviour under the 80th, 90th, and 97th percentile weather conditions. The authors compared fuel treatments that mechanically thinned the forest, paired mechanical thinning with burning, or only burned the forest. Spring versus fall burns were also compared. The authors used various forest management techniques to implement the mechanical treatments, including whole-tree removal, cut-to-length harvesting, or standard chainsaw and skidder or forwarder systems. All mechanical treatments removed all commercial materials from trees with DBH >20–25 cm that were harvested, though there was no significant removal of trees with DBH >76 cm at any site. Biomass or pulp trees (DBH 5–25 cm) were removed in only some forests, and mastication was used for the branches, tops, and 90% of small trees (DBH 2.5–25 cm) in only one forest in the central Sierra Nevada. At three of the five sites, mechanical treatments without fire increased surface fuel load significantly relative to the controls. Sites that experienced significant increase in surface fuel load used harvesting systems that left all activity fuels within the experimental units (i.e., the mastication site). The authors suggested that where trees are too small for sawn products and cannot be economically chipped and transported to a processing facility, subsidizing treatments or hauling costs should be considered if the corresponding decrease to fire hazard warrants the additional expense. Mechanical thinning paired with burning was the most effective at reducing the likelihood of passive crown fire at all five sites due to the increased vertical and horizontal canopy separation and the reduced surface fuels. Whole-tree harvesting was the most effective at reducing potential fire severity under severe weather conditions, but it is notable that sites that retained more large trees were more fire resistant. Spring burning alone resulted in the fewest significant changes to stand and fuel structure in this study. Fall burning reduced the density of trees with DBH <25 cm more so than spring burning, but spring burning retained more coarse woody debris. It is notable that there were more standing dead trees with DBH <15 cm following the burn only treatment relative to the mechanical thinning and burning treatment. These snags will eventually fall and increase fire hazard at those sites. The authors suggested that several burn only treatments may be necessary to achieve the desired conditions regarding potential fire behaviour in these forests. The authors found that while active crown fire potential was reduced by the mechanical only and mechanical and burning treatments, the burning only and mechanical and burning treatments reduced the potential of passive crown fire.

Kane et al. (2010) compared the effects of fuel treatment on understorey vegetation response in a second-growth ponderosa pine forest in the northern Sierra Nevada of California. The treatments compared were mastication only, hand removal only, mastication paired with tilling, mastication paired with prescribed fire, and a control. All treatments targeted the midstorey of the forest (i.e., small trees and shrubs). In the hand removal only treatment, hand-thinned midstorey biomass was manually removed after treatment. Mastication and hand-thinning treatments both occurred in May 2002. Tilling occurred one month after mastication, while prescribed fire occurred three years after mastication. Data was collected at all sites one year after the prescribed fire (four years after mastication). Every treatment resulted in greater plant cover relative to the control, suggesting that understorey vegetation responded to the release from shading, increase in growing space, and/or decrease in competition. The understorey was dominated by resprouting perennial shrubs. Plant recovery at the study sites may have been slower if the sites mainly consisted of species that germinate from seed. The small plot size and resulting increased edge effect may have also contributed to the increased plant recovery rates observed. While the midstorey was substantially reduced in all treatments, treatments did not result in a substantial decrease in canopy closure because overstorey conifers were retained. Across all treatments, the proportion of bare ground was positively correlated with understorey species diversity indices as more bare ground may allow for greater recruitment and establishment of individual plant species. The mastication and tilling treatment and the mastication and prescribed fire treatment directly increased the amount of bare ground. In contrast, the mastication only and hand removal only treatments maintained or decreased bare ground cover relative to the control. The greater amount of exposed and disturbed mineral soil promoted the germination of the shrub seed bank through scarification or chemical cues in the mastication treatments paired with tilling or prescribed fire. Conversely, litter cover and depth were negatively correlated with species richness. The control and the hand removal only and mastication only treatments had greater litter cover and depth. However, the additional organic material that was deposited on the forest floor following mastication did not reduce species richness, as the control and the hand removal only treatment did. The physical barriers caused by organic materials may have been offset by soil disturbance that was caused indirectly by the mastication equipment, which stimulated plant recovery. The shift in understorey plant composition in the treatments was associated with more bare ground, less litter cover, and lower canopy closure.

The mastication only and hand removal only treatments dramatically reduced midstorey vegetation but had little impact on understorey richness, compared to the control, without the subsequent consumption of the forest floor through prescribed fire. The mastication and prescribed fire treatment increased native species richness by 150% compared to the control, but it also increased non-native species richness and shrub seedling density. Mastication and tilling increased non-native forb density. The authors expressed great concern about fuel treatments increasing non-native plant species. Because the mastication and prescribed fire treatment was measured only one year after the treatment was complete, it is possible that non-native plant cover may rise in these treatment areas in the future. Research is needed on the long-term persistence of non-native species after fuel treatments. For reducing fire hazard, the mastication and prescribed fire treatment was likely the most effective, but the newly exposed mineral soil increased native and non-native plant diversity and shrub germination. This could compromise fire hazard reduction in the long term through the rapid addition of new surface and ladder fuels, calling into question the longevity of the treatments. To counteract this, substantial overstorey trees could be retained to maintain shading, which would lead to mortality of shrub seedlings. Alternatively, in a mastication only treatment, deep residual surface fuels can physically block the regeneration of understorey plants. In this study, litter depth was insufficient in blocking regrowth in mastication only treatments. Additionally, these surface fuels can contribute to substantial fire intensity, even after reducing midstorey trees, which act as ladder fuels. The authors concluded that many ecological and fire hazard trade-offs should be considered when planning a fuel treatment (Kane et al. [2010]).

Prescribed Fire

In Potts et al. (2010), the authors compared the effects of prescribed fire to those of mastication for three years after treatment, focusing on shrub cover, height, seedling density, and species composition, in a northern California chaparral ecosystem. Large mammal herbivory effects after treatment were also monitored. Mastication treatments had an average of only 43% shrub cover three years after treatment (relative to >90% before treatment). This was lower than the average shrub cover after prescribed fire (71%) because plants benefit from the immediate nutrient release after burning, while masticated sites release nutrients more slowly as the shredded biomass decays, resulting in slower regrowth. However, the results from this study and others in Mediterranean shrublands suggest that these ecosystems are highly resilient to disturbance, whether it be through fire or mechanical treatment. There was no significant difference in shrub height, species richness, or species composition between the prescribed fire and mastication treatments. Seedling density was initially higher in the prescribed fire treatments, but these treatments experienced more seedling mortality, especially during spring burning. This resulted in lower density of live seedlings in the third year after treatment. Refer to Potts et al. (2010)) for citations of each example mentioned.

Potts et al. (2010) reported seedling density was lower after treatment through all years, which was expected due to the number of fire-adapted species whose seeds need fire to be released from dormancy. Despite this, fire-adapted species resprouted in mastication sites, perhaps because the high solar heating of the residual shrublands triggered a release from dormancy. Seedlings experienced greater mortality in spring burning and mastication than in other treatments. This is likely because germinating plants have insufficient time and resources to establish roots that can withstand the heat of the oncoming summer months. Chamise, a more flammable shrub, was the more dominant shrub in all sites before treatment and remained so afterwards. Buckbrush, which has high nutritional value to browsing wildlife, was also present at the sites and had the highest recruitment in fall prescribed fire treatments. Buckbrush cover was still low after the third year because it relies on germination to regenerate, but this may not be a long-term detriment to the species. Once nitrogen levels go down in the years following prescribed fire, buckbrush seedlings should have a competitive advantage over other shrubs because of the ability of this species to fixate nitrogen, especially in a nitrogen-limited ecosystems such as chaparral. The season of treatment did not have a strong influence on shrub resprouting, but it had a significant impact on seedling density. Fall and winter prescribed fire treatments resulted in higher seedling density than other treatments. Fall burning best approximates the historical fire regime in this ecosystem, so this result was expected. However, the results of winter prescribed fire were not expected, as other studies have found that the moist soil during winter burns would hinder the success of certain species seedlings. Notably, fall mastication showed seedling recruitment by the third year for both chamise and buckbrush, despite the absence of fire. Deer herbivory most affected shrub height in the third year after mastication treatments. This may be due to the ease of movement deer have through areas that were masticated versus areas that were burned, and this would increase access to more resprouting shrubs. The results also show that large herbivores do not browse shrub seedlings extensively in the early years following disturbance, as seedling abundance was similar between enclosed and unenclosed areas. The authors concluded this publication by giving management implications. They stated that improving black tail deer (*Odocoileus hemionus*) habitat is likely best done by burning in the fall, since it encourages more buckbrush regeneration by the third year than the other treatments and their timing. It is notable that spring fire or mastication could be detrimental to seedling survival due to summer drought. Fire treatments are likely better for wildlife because of the faster, denser shrub regrowth. In contrast, mastication treatments are likely better than prescribed fire for longevity of treatments, due to a slower shrub regeneration rate, but that the fine fuel addition from mastication may increase the fire hazard.

7. Recommendations

Hvenegaard (2017) found that mulched fuels in jack pine and black spruce boreal forests in the Northwest Territories exhibited high surface fire intensity when exposed to experimental fire five years after treatment. When the author compared these results to experimental fire behaviour in fuel reduction treatments in similar forest types, the treatments were more effective at reducing fire behaviour. However, Hvenegaard noted that those treatments are typically more costly. A compromise would be to conduct a semi-mechanized fuel treatment that combines mulching with thinning and limbing by hand crews, and Hvenegaard (2017) recommended that this treatment type be explored for boreal ecosystems.

Kabzems et al. (2011) performed a literature review on the effects of applying wood chips on soils and vegetation throughout North America and formed a list of best management practices for British Columbia. They are as follows:

1. Ensure that biomass harvesting operations remove only material identified in the harvesting plan and that they do not decrease levels of organic matter (e.g., coarse woody debris) to below the requirements in existing guidelines and regulations for coarse woody debris retention.
2. Prevent re-entry of equipment by integrating timber harvest activities, in-woods biomass chipping operations, and woody debris disposal practices. This will prevent the need for expansion of existing roads and roadside work areas, and will minimize soil compaction and rutting (Figure 8 in Kabzems et al. [2011], not shown).
3. Place chipped material directly into containers used to transport chips to the processing facility or into a temporary storage container to maximize biomass recovery and avoid creating residual piles (Figure 9 in Kabzems et al. [2011], not shown).
4. Remove or redistribute large accumulations of woody material so that surface mulch is <8 cm deep to facilitate tree regeneration and forage production.
5. Avoid removing surface soil layers and litter layers during forest biomass harvesting. Although these layers represent a potential source of biomass, most soil functions take place in the top layers.

6. Note that sites in cooler climates, on fine-textured soils, and those with a high water table are at greater risk of detrimental effects from accumulations of chipped woody material than are well-drained, coarse-textured soils in warmer environments.
7. Be aware that accumulations of woody material >8 cm deep, particularly from aspen, could result in anaerobic soil conditions and become a source of phenolic compounds and/or reduced iron, which would be detrimental to plant growth and aquatic ecosystems that receive runoff from those woody accumulations.

Liu et al. (1996) summarized guidelines for storing and disposing of wood residue. Guidelines describing how to properly store wood chips as to diminish the problems of leachate can be found in the *Pulp and Paper Effluent Regulations* in the *Fisheries Act* and the BC *Waste Management Act.* Plans to store wood residue must be approved by the BC Ministry of Environment and Climate Change Strategy if the residue is to be stored on private or provincial Crown land, or by the appropriate federal authority if on federal Crown land. The climate, hydrogeology, and topography of a proposed wood residue storage site should be studied beforehand, and groundwater measurements should be taken during the wet season. Some soils can naturally decrease leachate by adsorbing dissolved organics it as it passes through (mineral soils do not adsorb much, whereas peat adsorbs a lot). However, these natural processes are unlikely to be able to handle storing large wood piles over the long term. To minimize the effects of leachate if storing wood residue close to a fish-bearing watercourse, wood piles should be located more than 100 m from the nearest surface water and should not be placed in a flood plain. They must also be located more than 300 m from a well used for human consumption and 15 to 50 m away from a property line. Wood piles should be monitored occasionally to monitor whether leachate is being produced. Additionally, some carbonaceous materials (such as ash from burned bark) have been used to detoxify some effluents, but this would likely be cost-effective only in small-scale operations. In the 1990s, leaving wood residue in fish-bearing waters or where leachate can enter fish-bearing waters could lead to a $300 000 fine, with the possibility of imprisonment for six months if additional offences are committed. In some circumstances, the fine may be as big as $1 000 000 with imprisonment of up to three years.

Fettig et al. (2006) studied the effects of chipping on bark beetle attraction in ponderosa pine forests of Arizona and California. The authors developed a series of recommendations based on their findings to reduce bark beetle attraction following chipping treatments. First, they recommend that chipping be done during periods of relative bark beetle inactivity, such as late summer to winter, to reduce attacks on residual trees. They also recommend that effort should be made to ensure that chips are separated from the boles of residual trees, and that if raking is used, it occurs immediately following the chipping operation to maximize its effectiveness at deterring bark beetles. The authors noted that treatments that promote drying and rapid decay of monoterpenes in slash should be considered before chipping. Further, treatment units should be designed to minimize the amount of edge per unit area as chipping may influence bark beetle attacks beyond the spatial scale of the treatments. It appears that a higher intensity of thinning and chipping is positively correlated with red turpentine beetle attacks, suggesting that the intensity of the attack increases with the intensity of the treatment.

8. Future Research

Bennet and Hvenegaard (2021) studied the use of hügelkultur, which translates to *mound culture*, as a means of managing debris. This technique decomposes woody material into humus by covering branches, logs, and finer debris with soil or mulch and allowing it to rot. These mounds are not compost piles, which decompose faster and produce nutrients and carbon. Instead, mounds act as carbon stores for years. They decompose slowly by anaerobic micro-organisms, providing habitat, water retention, and humus development (Bennet and Hvenegaard 2021). To test the effectiveness of the mounds against fire ignition and spread, the authors constructed piles of debris and other fuel treatment material in various sizes and configurations throughout their treatment area. Mounds are constructed, unnatural accumulations of fuel and, thus, do not have a representative fuel type for fire modelling. Consequently, the authors predicted that firebrand (ember) ignition or surface fire encroachment were the two primary factors to consider for fire spread. Mounds were designed with horizontally oriented fuels in small, dense piles to reduce air flow and flammability (Bennet and Hvenegaard 2021). This research is ongoing and may yield results that show mounds as another means of debris management for fuel mitigation.

Mitchell and Smidt (2019) mentioned baling, a fuel treatment that focuses on shrubs and small trees. This process involves a specialized towed baler that severs stems and creates round bales from woody biomass. Bundling was another method whereby bundlers pick up woody material and slash and compress it into composite residue logs, which are then easily carried by standard forestry machinery and can be cut to length as needed (Mitchell and Smidt 2019). The biomass in bundles is longer than in bales, but both can be ground once they are removed from the site, with bundles further supporting chipping processes (Mitchell and Smidt 2019). The authors also mentioned a "prototype one-pass system with a modified horizontal shaft-cutting head" that could cut, chip, and collect woody material for deposit into a roadside wagon, but additional information on this alternative was not provided.

Kreye et al. (2014) noted several research needs after performing a literature review of mastication treatments and fire behaviour across sites in the US. Some of the knowledge gaps that were identified included:

- Mastication and fire behaviour related to spatial heterogeneity of fuels at fuelbed, stand, and landscape scales.
- Empirical data describing fire behaviour in masticated fuels.
- Site-specific influences on fire behaviour (weather, wind, vegetation, etc.).
- Wildfire interaction with masticated fuels.
- Fire intensity and residency time and their ecological effects.
- Smouldering combustion and spot ignition in dense masticated fuels.
- Spatial variation of masticated fuels for modelling.
- Models that consider fuelbed depth and fuel load relationships, and custom models that estimate fuelbed characteristics, such as fuel load, particle size, depth, and fire behaviour.
- Particulate matter emissions from smouldering in masticated fuelbeds.
- Moisture dynamics in various fuel types, loads, depths, and composition.

Further, the authors suggested that future studies focus on quantifying fuel load, bulk density, surface-area-to-volume ratio, and plot-level variation, with estimates of where variation occurs (at which scale) (Kreye et al. 2014). More research needs are listed in Table 18 (Kreye et al. 2014).

Table 4
Potential science needs in masticated fire behavior research.

Science questions	Follow-up topics
Characterizing fuel beds	
What are the effects of mastication treatments on fuel beds?	Changes in fuel loading Changes in particle size Changes in fuel bed depth Characterizing the spatial and temporal variability in masticated fuel mixtures Characterizing the variability across fuel beds using different mastication machinery Validating fuel loading determination methods
How do masticated fuel beds change over time?	Comparisons to non-masticated fuel beds Changes in moisture content profiles Changes in decomposition rates (e.g., C/N ratios) Changes in species composition and biodiversity overstory growth and mortality Vegetation recovery rates and species trajectories
Characterizing fire behavior	
What are the effects of mastication on fire behavior?	Changes to fireline intensity Changes to the fire duration and rate of spread Drivers and patterns of post-frontal flaming Changes in the ratio of flaming and smoldering combustion Changes in the ratio of energy transfer methods (radiation, convection, and conduction) Changes in the generation of holdover embers Role of windspeed, moisture content, fuel bed depth, particle size, fuel mixtures, etc., in influencing fire behavior in masticated fuel beds
Characterizing fire effects	
What are differences in combustion products?	Changes in combustion completeness Changes in charcoal and black carbon production Changes in the apportionment of different gas species, aerosols, and particulate matter
What are longer-term impacts?	Impacts on vegetation mortality Impacts on soil properties Impacts on biogeochemical cycles Impacts on water infiltration and run off

Table 18. Future research in mastication (Table 4 from Kreye et al. [2014]).

Yukon Wildland Fire Management (2022) determined the following five areas for research based on the results of their study:

1. More people in each study are needed to adequately collect data related to fire behaviour during prescribed fires.
2. Portable weather stations should be used to gain better weather indices more often to correlate these with other metrics from the prescribed fires.
3. Follow-up prescribed fires should be conducted to determine how long the initial burn reduces flammability and how many burns would be required before the fuelbed would not carry a fire.
4. Data should be collected on fuelbed metrics, such as the difference in fuel size class distribution due to different estimation techniques, and on how compaction and moisture influence fire. This would help with further treatment prescriptions.
5. Further research should be conducted on counteracting blowdown after prescribed fire in a masticated fuelbed.

Baxter (n.d.) stated that further research is needed to determine what is best or what compromises may exist between treatments that reduce wildfire behaviour and increase or maintain wildlife suitability. Fernandes and Botelho (2003) stated that there is further need to evaluate the spatial arrangement of prescribed fire used in the landscape to maximize its benefits. Though Roberts et al. (2019) reviewed post-fire mulching rehabilitation treatments for their societal impacts, their findings may still be useful for this literature review. Through interviewing professionals working on wildfire mitigation activities in watershed partnerships in the US, the authors identified that a major knowledge gap is how mulching affects water quality or quantity. Roberts et al. (2019) recommended future research on this topic.

Finally, the authors of this extensive literature review recommend developing a publicly available database to aid in collecting data from mastication projects across BC. This would assist in sharing of lessons learned and challenges associated with implementation, what works well, what needs to be improved, and would result in cost savings. This would allow for future meta-analysis studies with data from different locations across the province. A database could be developed through an online or mobile phone application and made accessible to those involved in mastication. It could allow for sharing of results and successes.

Additional exploration of the literature regarding the interaction of prescribed fire and pile burning could yield further information to consider in these fuel management approaches in BC along with testing treatments and methods with actual wildland fire in variable conditions. As the fire season continues to extend earlier in the spring and later in the fall with sustained drought conditions and increased fire behaviour and presence across the landscape, there are significant opportunities to collect data and gain increased understanding of the interaction between fuel management methods and wildland fire. By capturing this data, analysing it, and reporting out through peer-review processes, an increased base of knowledge may continue to inform future fuel management methods in the province of BC.

FPInnovations has contributed an extensive foundation of research in fuel management and operational implementation. Their library provides a valuable resource for fuel management practitioners: https://library.fpinnovations.ca/.

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