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## Method Article

# A novel approach to fuel biomass sampling for 3D fuel characterization



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## A B S T R A C T

Surface fuels are the critical link between structure and function in frequently burned pine ecosystems, which are found globally (Williamson and Black, 1981; Rebertus et al., 1989; Glitzenstein et al., 1995) [1–3]. We bring fuels to the forefront of fire ecology through the concept of the Ecology of Fuels (Hiers et al. 2009) [4]. This concept describes a cyclic process between fuels, fire behavior, and fire effects, which ultimately affect future fuel distribution (Mitchell et al. 2009) [5]. Low-intensity surface fires are driven by the variability in fine-scale (sub-m level) fuels (Loudermilk et al. 2012) [6]. Traditional fuel measurement approaches do not capture this variability because they are over-generalized, and do not consider the fine-scale architecture of interwoven fuel types. Here, we introduce a new approach, the “3D fuels sampling protocol” that measures fuel biomass at the scale and dimensions useful for characterizing heterogeneous fuels found in low-intensity surface fire regimes.

- Traditional fuel measurements are oversimplified, prone to sampling bias, and unrealistic for relating to fire behavior (Van Wagner, 1968; Hardy et al., 2008) [7,8].
- We developed a novel field sampling approach to measuring 3D fuels using an adjustable rectangular prism sampling frame. This voxel sampling protocol records fuel biomass, occupied volume, and fuel types at multiple scales.
- This method is scalable and versatile across ecosystems, and reduces sampling bias by eliminating the need for ocular estimations.

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## A R T I C L E I N F O

*Method name:* 3D fuels sampling protocol

*Keywords:* Surface fire, Low-intensity fire, Forest fire, Longleaf pine, *Pinus palustris*, Fuel load, Bulk density, Volume, Fine scale, Fuel heterogeneity, Fuel sampling

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## Specifications Table

<b>Subject Area</b>	Environmental Science
<b>More specific subject area:</b>	surface fuels, fuel distribution
<b>Method name:</b>	3D Fuels Sampling Protocol
<b>Name and reference of original method</b>	D. Mueller-Dombois, H. Ellenburg, Aims and methods of vegetation ecology. Wiley and Sons, New York. (1974) J. K. Brown, "Handbook for inventorying downed woody material" GTR-INT-16 (USDA Forest Service, Intermountain Research Station, Ogden, Utah, 1974). J. K. Hiern, J. J. O'Brien, R. J. Mitchell, J. M. Grego, E. L. Loudermilk, The wildland fuel cell concept: an approach to characterize fine-scale variation in fuels and fire in frequently burned longleaf pine forests. <i>International Journal of Wildland Fire</i> 18, 315 (2009).
<b>Resource availability</b>	

## Method details

### *Moving away from traditional surface fuel measurements*

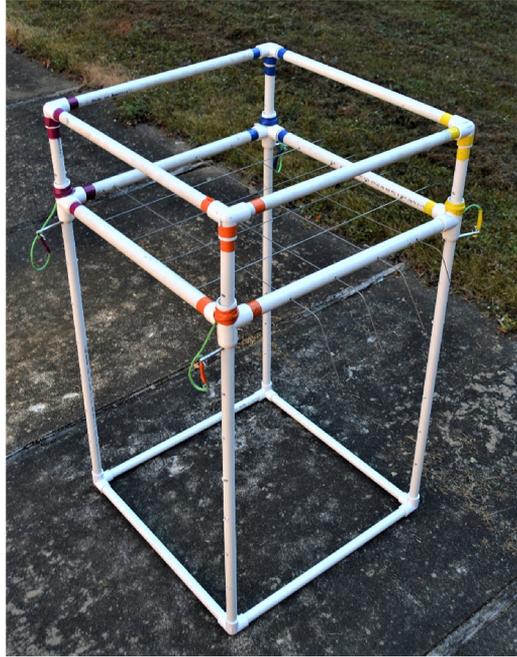
The concept of the Ecology of Fuels [5] was developed to characterize and connect the variations in fuels which are relevant to similar scales of fire behavior and subsequent fire effects. We apply this concept here to a new field sampling approach within a frequently burned forest, where fuels and fire vary at fine-scales, or within sub-m spatial variability [2,4,6].

Traditional surface fuels measurements were developed to support coarse grain and point-based fire behavior modeling, but do not include a full range of variability or spatial non-uniformity typically found in surface fuelbeds [1,8], particularly those found in frequently burned pine ecosystems [3,4]. These approaches are designed to report management unit averages that give broad landscape-scale assessments of load [9,10]. Common direct measurements are tallies of down woody fuels along planar transects [11] coupled with destructive biomass sampling, known as "clip plots" [12]. Indirect methods include visual cover estimates in plots or comparisons with photographs of known fuel loads or types [9,13]. These methods provide estimates of characteristics—such as fuel load, bulk density, and packing ratios—that are useful for predicting fire behavior at the stand level [14–16], but inherently require unrealistic assumptions regarding shrub and grass bulk densities that oversimplify these outputs [7].

Traditional methods are not suitable for estimating fine-scale fuel heterogeneity that are important for simulating within-stand fire behavior [17], notwithstanding their subjective nature and oversimplification of architecture and volume [4,18,19]. To characterize three-dimensional fine-scale variation in fuel characteristics particularly relevant to surface fire regimes, we introduce here a novel voxel sampling approach, where we built a 3D rectangular sampling frame that allows fuels data to be collected in the field at three different scales—entire plot ( $0.25\text{ m}^3$ ), stratum ( $0.025\text{ m}^3$ ), down to individual voxels ( $0.001\text{ m}^3$ ). Our method known as the 3D fuels sampling protocol is informed by advancements from in situ terrestrial laser scanning [18,20–22] and high resolution fuelbed simulations [23] that demonstrate clear relationships between occupied volume or surface area with 2D measured biomass. However, there are questions related to where mass is concentrated and distributed within the fuelbed that cannot be answered by remote sensing and simulation without a reciprocal validation data set. This method seeks to ultimately bridge this knowledge gap.

### *3D sampling frame*

A 3D rectangular sampling frame (Fig. 1) designed to be light weight, portable, and easily assembled in the field was constructed of PVC and outlines the sampling area that is 0.5 m in width by 0.5 m in length by 1 m in height. The frame is subdivided into ten 10 cm vertical sampling strata ranging from 0 to 100 cm in height. These strata are defined as 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 40–50 cm, 50–60 cm, 60–70 cm, 70–80 cm, 80–90 cm, 90–100 cm where 0 cm is ground level and 100 cm is top of the plot. Each 10 cm stratum contains twenty-five  $10\text{ cm}^3$  voxels, totaling 250 voxels



**Fig. 1.** 3D rectangular sampling frame.

that are distributed over the frame's sampling volume of  $250,000\text{ cm}^3$  or  $0.25\text{ m}^3$ . The individual voxels are  $.001\text{ m}^3$  and measure  $10\text{ cm} \times 10\text{ cm} \times 10\text{ cm}$ . There are 25 voxels ( $5 \times 5$ ) per stratum and a total of 250 voxels per plot. The frame can be constructed to include taller vegetation, but this becomes cumbersome in the field. Furthermore, in frequently burned ecosystems, the complex fuels of interest are found within this 1-m range, both vertically and horizontally [4,6].

An additional PVC square was built to simplify the sampling process down the sampling frame (i.e. between each stratum). It was designed to move vertically along the legs of the rectangular sampling frame. PVC tee fittings held with hitch pins inserted into drilled holes through the 3D rectangular sampling frame legs permits the PVC square to be lowered every 10 cm. Removable metal rods (8 total) are horizontally inserted into drill holes of the PVC square at 10 cm intervals to define each voxel space when sampling.

To build the rectangular frame, you will need at least:

- 8 PVC 90-degree side outlet elbows to connect the PVC pipe pieces
- PVC pipe pieces for the legs
- 8 PVC pipe pieces for form the top and bottom squares of the rectangle

To build the sliding square frame, you will need at least:

- 4 hitch pins
- 4 four-way tee PVC fitting
- 4 PVC pipes
- 8 small metal rods

It is recommended to use PVC pipe with a PSI 600 rating as this lends durability and strength to the frame without compromising the light weight of the frame.

Attaching PVC elbows and tee fittings to PVC pipe will increase the final length of the piece, therefore, fittings should be attached for all measurements including cutting and drilling. Additionally,

to ensure that the rectangular frame and square frame were quickly and constantly assembled, four different color tapes were used to identify each side of the frame and to distinguish between the top and bottom of the frame.

To ensure mobility of the square frame along the legs of the rectangular frame, the 4-way tee PVC fittings should have a larger inside diameter than the outside diameter of the rectangular frame legs.

*Fuels sampling*

*Datasheets*

Prior to field sampling, a datasheet (Fig. 2) is created with all fuel types numbered by voxel number (1–250, Fig. 3) to record (presence/absence) occupied volume for each fuel type. For the occupied volume data, example fuel types used for a longleaf pine (*Pinus palustris* Mill.) woodland include 1–10 hour fuels, 100–1000 hour fuels, general pine litter (e. g. longleaf, shortleaf and/or loblolly pine), wiregrass/bunchgrass, other graminoids, shrubs, volatile shrubs, forbs, pine cones, deciduous oak litter, evergreen oak litter, and longleaf pine litter (Fig. 2). Note that these fuel types were specific for our study area that typically burn every 1–3 years. Fuel types should be designated specifically for each study area (ecosystem, forest type) and created before sampling begins in the field.

*Location and orientation of the sampling frame*

Plot locations are chosen based on data needs, questions of interest, fuel types or configurations of fuel types of interest, or possible associations being made with other instrumentation in the field. At each chosen plot location, the frame is oriented to the designated plot area (0.25 m<sup>2</sup>). The 3D rectangular frame is centered and orientated so the first voxel for each stratum is the most northwest voxel. Orientation is not required, but useful for consistency among sampling plots, relating to other nearby field measurements or equipment, or relating to data from remote sensing instrumentation, such as GPS, terrestrial laser scanning or infrared thermography. The base of the rectangular frame is

Plot No #:	Collectors:																									Date:		
<b>Voxel</b>	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Height: 0-10 cm		
1-10 hr fuel																											Random #s: (1-20) (1-4)	
100-1000 hr fuel																												
Other Pine litter																												
Wiregrass/Bunchgrass																											Clip Voxels:	
Other Graminoids																												
Shrubs																												
Vol. shrubs																												
Forbs (and Forb Litter)																												
Empty																												
Pine Cones																												
Dec. Oak litter																												
Ever Oak litter																												
LLP litter																												
LLP seedling																												
Other (state)																												
<b>Voxel</b>	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	Height: 10-20 cm		
1-10 hr fuel																												Random #s: (1-20) (1-4)
100-1000 hr fuel																												
Other Pine litter																												
Wiregrass/Bunchgrass																											Clip Voxels:	
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Empty																												
Pine Cones																												
Dec. Oak litter																												
Ever Oak litter																												
LLP litter																												
LLP seedling																												
Other (state)																												

Fig. 2. Page 1 of the field sampling datasheet, representing the bottom two strata of each plot.

0-10 cm					10-20 cm					20-30 cm				
1	6	11	16	21	26	31	36	41	46	51	56	61	66	71
2	7	12	17	22	27	32	37	42	47	52	57	62	67	72
3	8	13	18	23	28	33	38	43	48	53	58	63	68	73
4	9	14	19	24	29	34	39	44	49	54	59	64	69	74
5	10	15	20	25	30	35	40	45	50	55	60	65	70	75

30-40 cm					40-50 cm					50-60 cm				
76	81	86	91	96	101	106	111	116	121	126	131	136	141	146
77	82	87	92	97	102	107	112	117	122	127	132	137	142	147
78	83	88	93	98	103	108	113	118	123	128	133	138	143	148
79	84	89	94	99	104	109	114	119	124	129	134	139	144	149
80	85	90	95	100	105	110	115	120	125	130	135	140	145	150

60-70 cm					70-80 cm					80-90 cm				
151	156	161	166	171	176	181	186	191	196	201	206	211	216	221
152	157	162	167	172	177	182	187	192	197	202	207	212	217	222
153	158	163	168	173	178	183	188	193	198	203	208	213	218	223
154	159	164	169	174	179	184	189	194	199	204	209	214	219	224
155	160	165	170	175	180	185	190	195	200	205	210	215	220	225

90-100 cm				
226	231	236	241	246
227	232	237	242	247
228	233	238	243	248
229	234	239	244	249
230	235	240	245	250

Fig. 3. Voxel orientation for each stratum.

placed on the ground at mineral soil so all aboveground components (e.g. live vegetation, litter, coarse woody debris, stems, etc.) will be collected.

#### Occupied volume data sampling

A top-down sampling approach is implemented to collect occupied volume data and aboveground biomass. At each stratum, the metal rods are particularly useful because they are inserted horizontally in the square frame penetrating the vegetation across the stratum. The sampling protocol can be done in designated pre-fire and post-fire plots to estimate fuel consumption and residual fuel structure.

From 100 cm down, the sliding square frame is lowered to the highest stratum that contains vegetation. If a stratum does not contain vegetation, it is noted on the data sheet. Since the removable metal rods in the sliding square represent the bottom of the stratum, the biomass in that stratum will be 10 cm or less above the metal rods.

Within each stratum, each voxel cell is sampled (presence/absence) for fuel type on the datasheet. Note that each voxel has the potential to encompass multiple fuel types. Also note that the height of fuels is collected as a function of voxel cell position. This reduces errors in measurement as every cell has a known height (stratum height) and position (voxel) that allows for generation of spatially explicit and three-dimensional fuel models (see graphical abstract).

#### Destructive biomass sampling

At each stratum, after the occupied volume data is recorded on the datasheet, biomass is destructively harvested by clipping and bagging the material. After that entire stratum is clipped and bagged, the sliding square frame is lowered 10 cm to the next height stratum. The occupied volume and biomass collection method is repeated until mineral soil is reached. Care is taken to not collect duff, unless this is of interest to the collector. At this 0–10 cm height stratum, stems are harvested as close to the soil as possible. Harvesting large fuels (downed log) are at the discretion of the sampler.

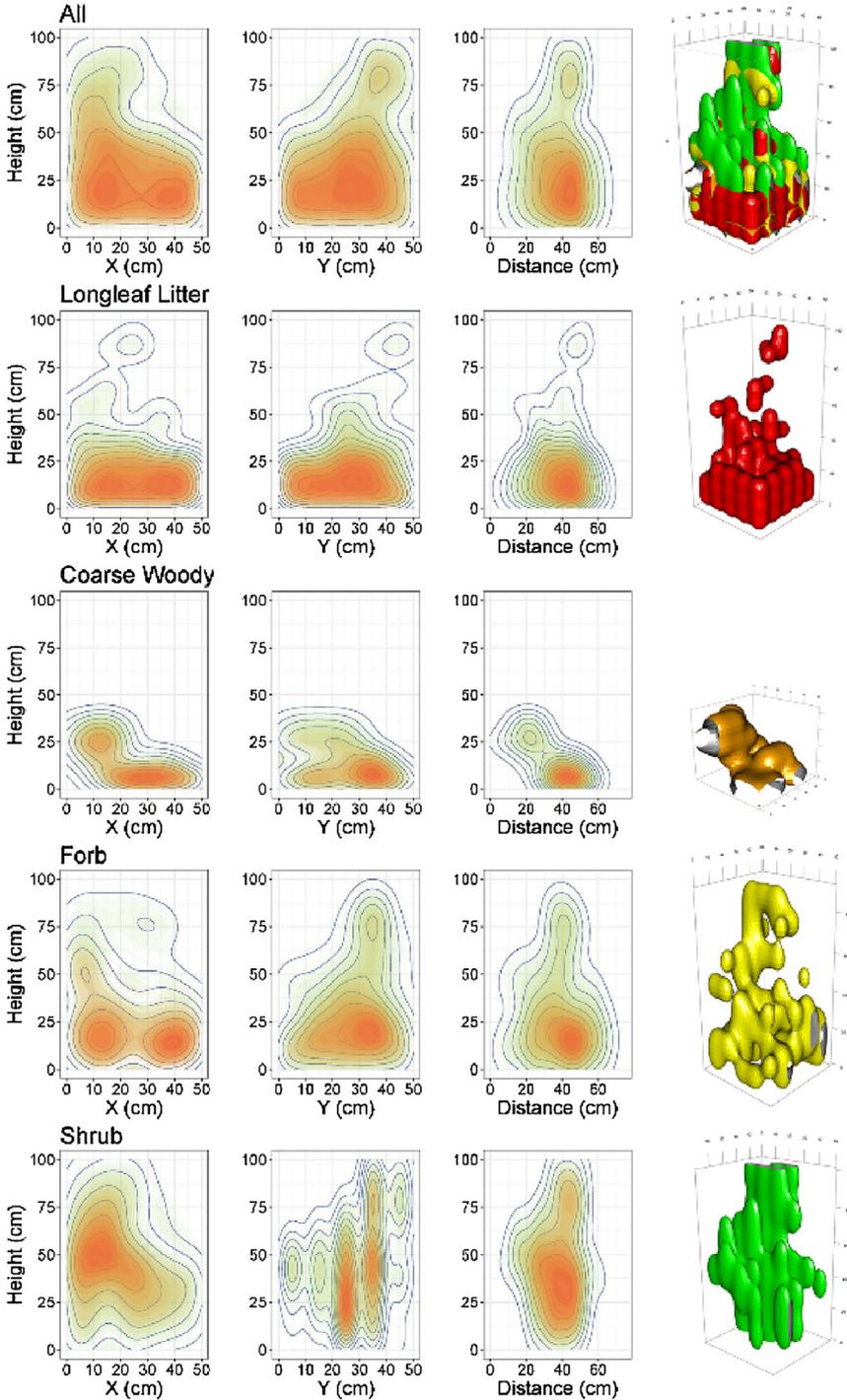


Fig. 4. Example of fuel distribution, as represented by occupied volume of various fuel types through the 3D fuelbed in 0.25 m<sup>3</sup> space as sampled with this method.

The collected biomass is dried at 70 °C until the weight of the sample no longer changes. For most material, this requires 48 h of drying time. Some of the heavier fuels may require 72–96 hours of drying time. Once dry, the weight is recorded for each sampled stratum (0.025 m<sup>3</sup>) and plot (0.25 m<sup>3</sup>). This fuel drying protocol (temperature, length of drying) is similar to traditional approaches [12,10].

The entire field sampling process takes approximately 30 min to 1.5 h per plot depending on the amount, height, and complexity of vegetation. With the frame in place, pictures of the plot can be taken before, during, and after the plot has been destructively harvested for quality assurance purposes.

Biomass sampling at the voxel level (0.001 m<sup>3</sup>) is obtainable, but does increase sampling and laboratory processing time considerably. It is suggested to take a representative sample of the voxels. For example, random sampling five voxels at each stratum results in sampling 20% of the entire rectangular prism area.

Fig. 4 is an illustration of how an individual plot can be dissected to fuel types through the fuelbed. It illustrates the occupied volume distribution of all fuels in the plot combined, and broken down by specific fuel types.

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