

A Compound from Smoke That Promotes Seed Germination

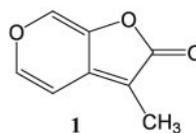
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Smoke derived from burning plant material has been found to increase germination of a wide range of plant species from Australia, North America, and South Africa (1). We now report the identity of a compound, present in plant- and cellulose-derived smoke, that promotes germination of a variety of smoke-responsive taxa at a level similar to that of plant-derived smoke water.

The separation of the bioactive agent was facilitated by bioassay-guided fractionation with *Lactuca sativa* L. cv. Grand Rapids (2) and two smoke-responsive Australian species, *Conostylis aculeata* R. Br. (Haemodoraceae) and *Stylidium affine* Sonder. (Stylidiaceae) (3). Extensive fractionation of the relatively less complex, cellulose-derived smoke (from combustion of filter paper) resulted in the isolation of a compound that promotes seed germination (4). The structure of this compound was elucidated from mass spectrometry (MS) and spectroscopic data obtained by

¹H, ¹³C, and two-dimensional (homonuclear correlation, heteronuclear single-quantum coherence, heteronuclear multi-bond correlation, and nuclear Overhauser effect spectroscopy) nuclear magnetic resonance (NMR) techniques. Confirmation of the structure as the butenolide 3-methyl-2H-furo[2,3-c]pyran-2-one (1) (Scheme 1) was achieved by synthesis. The presence of 1 in extracts of plant-derived smoke was confirmed by gas chromatography–MS analysis.

We compared the activity of the synthetic form of the butenolide (1) with that of plant-derived smoke water by testing it at a range of concentrations with the three bioassay species. The results (Fig. 1) show that 1 stimulated the germination of each test species to a level similar to that achieved with plant-derived smoke water. Furthermore, activity is demonstrated at very low concentrations (<1 ppb, 10⁻⁹ M). Testing of



Scheme 1.

other smoke-responsive Australian species and smoke-responsive South African (e.g., *Syncarpha vestita*) and North American (e.g., *Emmenanthe penduliflora* and *Nicotiana attenuata*) species has further confirmed the activity of 1 (table S1).

The butenolide (1) conforms to the necessary ecological attributes of smoke that is produced from fires in natural environments. For example, the butenolide (1) is stable at high temperatures (its melting point is 118° to 119°C), water-soluble, active at a wide range of concentrations (1 ppm to 100 ppt), and capable of germinating a wide range of fire-following species. The butenolide is derived from the combustion of cellulose, which, as a component of all plants, represents a universal combustion substrate that would be present in natural fires.

Given the broad and emerging use of smoke as an ecological and restoration tool (1), the identification of 1 as a main contributor to the germination-promoting activity of smoke could provide benefits for horticulture, agriculture, mining, and disturbed-land restoration. In addition, the mode of action and mechanism by which 1 stimulates germination can now be investigated. In this context, it is useful to note that the natural product (+)-strigol, which promotes the germination of the parasitic weed *Striga* (5), is active at similar concentrations (10⁻⁹ M) and contains a butenolide moiety and additional conjugated functionality similar to those in 1.

References and Notes

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- Materials and methods are available as supporting material on Science Online.
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Supporting Online Material

www.sciencemag.org/cgi/content/full/1099944/DC1
Materials and Methods
Table S1

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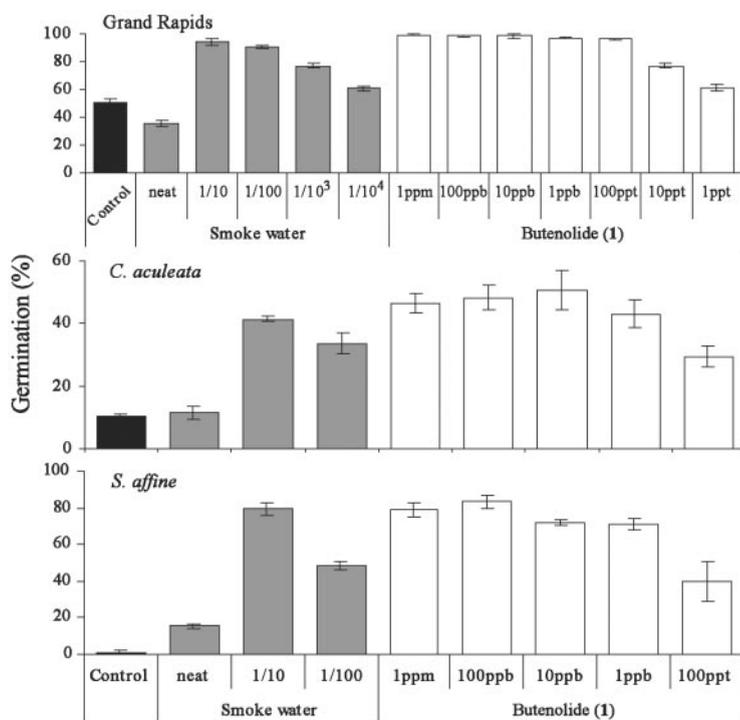


Fig. 1. Comparison of the germination response of plant-derived smoke water and butenolide (1) at different concentrations with three smoke-responsive species: Grand Rapids lettuce, *C. aculeata*, and *S. affine*. Water served as the control, and "neat" refers to undiluted smoke water. Values are means of three replicates \pm SE.

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