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Smoke emissions due to burning of green waste in the Mediterranean area: Influence of fuel moisture content and fuel mass

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HIGHLIGHTS

- Fuel moisture content lowers the combustion efficiency and heat release rate.
- Burning phase influence on emissions cannot be determined by EFs vs. MCE.
- Increasing mass raises the EFs of CO and CH_4 but reduces EFs of CO_2 and NOx.
- Increasing fuel moisture content rises the EFs of CO, CH_4, NH_3, and NMOC.

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ABSTRACT

The aim of this study was to investigate emission characteristics in relation to differences in fuel moisture content (FMC) and initial dry mass. For this purpose, branches and twigs with leaves of *Cistus monspeliensis* were burned in a Large Scale Heat Release apparatus coupled to a Fourier Transform Infrared Spectrometer. A smoke analysis was conducted and the results highlighted the presence of CO_2, H_2O, CO, CH_4, NO, NO_2, NH_3, SO_2, and non-methane organic compounds (NMOC). CO_2, NO, and NO_2 species are mainly released during flaming combustion, whereas CO, CH_4, NH_3, and NMOC are emitted during both flaming and smoldering combustion. The emission of these compounds during flaming combustion is due to a rich fuel to air mixture, leading to incomplete combustion. The fuel moisture content and initial dry mass influence the flame residence time, the duration of smoldering combustion, the combustion efficiency, and the emission factors. By increasing the initial dry mass, the emission factors of NO, NO_2, and CO_2 decrease, whereas those of CO and CH_4 increase. The increase of FMC induces an increase of the emission factors of CO, CH_4, NH_3, NMOC, and aerosols, and a decrease of those of CO_2, NO, and NO_2. Increasing fuel moisture content reduces fuel consumption, duration of smoldering, and peak heat release rate, but simultaneously increases the duration of propagation within the packed bed, and the flame residence time. Increasing the initial dry mass, causes all the previous combustion parameters to increase. These findings have implications for modeling biomass burning emissions and impacts.

1. Introduction

Forest fires are a major and continuing threat to human life, health, and livelihoods; to economic development; and to the environment. Fuel management is defined as "the act or practice of controlling flammability and reducing resistance to control of wildland fuels through mechanical, chemical, biological or manual means, or by fire" (Food and Agriculture organization of the United Nations, 2007). To modify the load and the arrangement of both live and dead fuels, different techniques can be used. They include, for example, firebreaks, fuelbreaks, and fuel reduction through clearing, prescribed burning, or pruning. Most of these fuel management options involve cutting vegetation. To eliminate this green waste, several options exist: grinding on site, moving to a recycling center, or open burning. To limit pollution, several states in the world regulate open burning. However, this practice is still often used in Europe and in particular, in Mediterranean areas. The emissions due to green waste burning, and more generally biomass burning, are a significant source of gases and aerosols in the atmosphere. These include greenhouse gases (such as carbon dioxide

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Nomenclature

AHC	Ascending hierarchical classification
C	Mass concentration (kg/m^3)
E	Heat release per unit mass of O_2 consumed (J/kg)
EF	Emission factor (g/kg)
F_c	Mass fraction of carbon (−)
FC	Fuel consumption (−)
FMC	Fuel moisture content on dry basis (%)
FTIR	Fourier transform infrared spectrometer
HHV	Higher heating value (kJ/kg)
HRR	Heat release rate (W)
I	Laser beam intensity (Cd)
k	Light extinction coefficient (m^{-1})
k_t	Constant determined via a propane burner calibration (−)
k_p	Constant of the bi-directional probe (−)
LHV	Lower heating value (kJ/kg)
m	Mass (kg)
MCE	Modified combustion efficiency (−)
NMOC	Non-methane organic compounds
NDIR	Non-dispersive infrared gas analyzer
$\dot{n}^{\circ}_{O_2}$	Molar flow rate of O_2 in incoming air (mol/s)
$\dot{n}_{O_2}$	Molar flow rate of O_2 in the exhaust duct (mol/s)
PCA	Principal component analysis
PHRR	Peak of the heat release rate (W)
SPR	Smoke production rate (m^2/s)
t	Time (s)
T	Temperature (K)
THR	Total Heat Release (J)
TSP	Total smoke production (m^2)
$\dot{V}$	Standard flow rate in the exhaust duct at 298 K (m^3/s)
W	Molecular weight (kg/mol)
X	Mole fraction (−)

Greek symbols

α	Expansion factor for the fraction of the air that was depleted of its oxygen (−)
Δ	Excess mixing ratio (mol/m^3)
ΔE_{ign}	Energy released by heptane during ignition (J)
ΔP	Pressure drop across the bi-directional probe (Pa)
ϕ	Oxygen depletion factor (−)
ρ_0	Density of dry air at 298 K and 1 atm (kg/m^3)
σ_s	Specific extinction area (m^2/kg)

Subscript

0	Initial value
a	Aerosol
ambient	Ambient
air	Air
b	Burned
dry	Dry
f	Final
fl	Flaming combustion
fuel	fuel
g	Gas in the duct
i	Initial
k	Compound k
O_2	Oxygen
p	Propagation phase of the flame in the pile
plume	Plume
r	Residual after the combustion
sm	Smoldering combustion
wet	Wet

Superscript

$\circ$	Incoming air
∞	Ambient

or methane), photochemically reactive compounds (such as carbon monoxide, volatile organic compounds, or nitrogen oxides), and particulate matter (Andreae and Merlet, 2001; Akagi et al., 2011). The greenhouse gases and the particulate matter directly influence climate and have impacts on humans (Crutzen and Andreae, 1990; Reid et al., 2005). CO, hydrocarbons, and NOx are the starting ingredients for the formation of ozone (Crutzen and Andreae, 1990). In addition, particulate matter and volatile organic compounds affect human health because they can induce cancer, irritation, or cardiovascular and respiratory diseases (Lewtas, 2007). Knowing the composition of the emissions released by biomass burning is therefore an important public health issue.

One way to study the fire emissions and their impacts involves the use of numerical models. However, these models require not only data such as burned area or fuel load but also reliable emission factors for both gaseous and particulate emissions, which depend on fuel and burning conditions. In the literature, there are a significant number of publications that report emission factors for burning different kinds of biomass (Ward and Hardy, 1991; Goode et al., 1999; Andreae and Merlet, 2001; McMeeking et al., 2009; Soares Neto et al., 2009; Urbanski et al., 2009; Yokelson et al., 2009; Akagi et al., 2011; Simpson et al., 2011). These studies present emission factors of various ecosystem types (savanna, grassland, tropical, extratropical, or boreal forests) and human activities. Concerning Mediterranean vegetation, the most significant works on this subject are Ciccioli et al., 2001; Alves et al., 2010, 2011a, 2011b; Vicente et al., 2011; Evtyugina et al., 2013; Garcia-Hurtado et al., 2013, 2014; Kostenidou et al., 2013; Santoni et al., 2015; and Chiaramonti et al., 2016. The measurements of emission factors were obtained either during actual fires, prescribed burnings, or laboratory experiments. At field scale, different sampling strategies were used (e.g., such as ground-based measurements and instruments on masts or in aircraft. At laboratory scale, the smoke was usually sampled in the exhaust duct of the combustion products. Field studies have the advantage of measuring emissions from an actual fire. However, the number of measurements is generally limited and the data collected represent a snapshot in time and space. The operating conditions at the laboratory scale are generally far from those encountered in real fires. However, laboratory experiments contribute to the overall understanding of the emissions from biomass burning by focusing on the particular influence of specific parameters. The emissions due to biomass burning depend on the type and state (alive or dead, dry or wet) of fuel and on the fire characteristics. The most significant parameters are the fuel composition, the fuel moisture content, the fuel load, the fire intensity, the wind conditions, the combustion type (flaming or smoldering combustion), and the spreading mode (differentiating heading versus backing fire spread) (Evtyugina et al., 2013; Surawski et al., 2015). Despite the number of studies on biomass burning at laboratory or field scales, there remains a significant source of uncertainty on the estimation of fire emissions. In general, the studies on biomass burning focus on the variability of the