Atmospheric Environment 126 (2016) 145–152

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Effect of bark beetle (*Ips typographus* L.) attack on bark VOC emissions of Norway spruce (*Picea abies* Karst.) trees

Rajendra P. Ghimire [a, *], Minna Kivimäenpää [a], Minna Blomqvist [b], Toini Holopainen [a], Päivi Lyytikäinen-Saarenmaa [b], Jarmo K. Holopainen [a]

[a] Department of Environmental Science, Kuopio Campus, University of Eastern Finland (UEF), P.O. Box 1627, FI–70211, Kuopio, Finland
[b] Department of Forest Sciences, University of Helsinki, P.O. Box 27, FI-00014, University of Helsinki, Finland

HIGHLIGHTS

- Beetle attack increases the emissions of MTs but decreases those of several SQTs.
- α-Pinene, camphene and myrcene are the most responsive bark beetle induced MTs.
- α-Pinene emission has positive correlation with mean trap catch of bark beetles.

GRAPHICAL ABSTRACT

ARTICLE INFO

Article history:
Received 22 June 2015
Received in revised form
28 October 2015
Accepted 23 November 2015
Available online 26 November 2015

Keywords:
Norway spruce
BVOC emission
Bark beetle
Outbreak
Resin flow
Pheromone trap

ABSTRACT

Climate warming driven storms are evident causes for an outbreak of the European spruce bark beetle *(Ips typographus* L.) resulting in the serious destruction of mature Norway spruce (*Picea abies* Karst.) forests in northern Europe. Conifer species are major sources of biogenic volatile organic compounds (BVOCs) in the boreal zone. Climate relevant BVOC emissions are expected to increase when conifer trees defend against bark beetle attack by monoterpene (MT)-rich resin flow. In this study, BVOC emission rates from the bark surface of beetle-attacked and non-attacked spruce trees were measured from two outbreak areas, Iitti and Lahti in southern Finland, and from one control site at Kuopio in central Finland. Beetle attack increased emissions of total MTs 20-fold at Iitti compared to Kuopio, but decreased the emissions of several sesquiterpenes (SQTs) at Iitti. At the Lahti site, the emission rate of α-pinene was positively correlated with mean trap catch of bark beetles. The responsive individual MTs were tricyclene, α-pinene, camphene, myrcene, limonene, 1,8-cineole and bornyl acetate in both of the outbreak areas. Our results suggest that bark beetle outbreaks affect local BVOC emissions from conifer forests dominated by Norway spruce. Therefore, the impacts of insect outbreaks are worth of consideration to global BVOC emission models.

1. Introduction

Biogenic volatile organic compounds (BVOCs) refer to organic atmospheric trace gases and non-methane hydrocarbons that are emitted by plants or other organisms (Laothawornkitkul et al., 2009). The BVOCs comprise four main compound categories: isoprene (C_5H_8), monoterpenes ($C_{10}H_{16}$), other reactive VOCs and other less reactive VOCs (Laothawornkitkul et al., 2009). Globally, BVOCs with an amount of 1150 Tg (C) y^{-1} constitute more than 50% of all atmospheric VOCs (Guenther et al., 1995; Hallquist et al.,

* Corresponding author.
E-mail address: rajendra.ghimire@uef.fi (R.P. Ghimire).

http://dx.doi.org/10.1016/j.atmosenv.2015.11.049

2009). The BVOC emissions from plants increase with abiotic stresses (e.g. high temperature, high solar radiation) alone or together with insect herbivore and pathogen attacks. The BVOCs function in communication with other plants and organisms (Peñuelas and Llusia, 2003; Heil and Karban, 2010; Holopainen and Gershenzon, 2010; Loreto and Schnitzler, 2010), and play a role in plant growth, development, reproduction, and defense (Pen;̃uelas and Llusia, 2003; Loreto and Schnitzler, 2010).

The BVOCs from natural vegetation may significantly alter the chemistry of the lower atmosphere. Photochemical reactions of BVOCs and nitrogen oxides (NOx) result in the formation of ozone (O_3) (Pinto et al., 2010). The BVOCs react with hydroxyl (OH) and nitrate (NO_3) radicals and O_3 in the troposphere (Atkinson and Arey, 2003), and they form a large amount of extremely low-volatility vapors and result in the formation of secondary organic aerosols (SOA) on condensation (Virtanen et al., 2010; Ehn et al., 2014). The BVOCs contribute up to 90% to SOA formation (90 Tg (C) y^{-1}) (Kanakidou et al., 2005; Hallquist et al., 2009). Bergström et al. (2014) estimated that the biotic stress-induced BVOC emissions from European forest ecosystems occasionally contribute more to SOA production than the constitutive emissions. Resin-storing conifers are important emission sources of reactive monoterpenes (Ghimire et al., 2013). Laboratory chamber experiments showed that feeding by pine weevils (*Hylobius abietis* L.) increased VOC emissions from Scots pine and Norway spruce seedlings by 10–50 fold resulting in 200–1000 fold increases in SOA masses formed via ozonolysis by added ozone (Joutsensaari et al., 2015). In a modelling study, Berg et al. (2013) reported that BVOCs induced by mountain pine beetle (*Dendroctonus ponderosae* Hopkins) from lodgepole pine (*Pinus contorta var. Latifolia* Engelm.) and other bark beetle (species not identified) from Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) trees may lead up to a 3-fold increase in atmospheric SOA. Aerosols affect the radiative balance of Earth's atmosphere by scattering and absorbing solar and terrestrial radiation (Boucher et al., 2013). Significant aerosol nucleation events have been detected in the boreal environment also in winter and spring (Kulmala et al., 1998), when BVOCs participate actively in atmospheric processes. However, a global chemical transport model suggests that the summertime source of Aitken mode (30–110 nm) and nucleation mode (110–700 nm) aerosols may contribute more to cloud condensation nuclei than the accumulation mode aerosols (110–700 nm) in spring season (Korhonen et al., 2008).

European boreal forests, dominated by conifers, are characterized by large BVOC emissions. The average total BVOC emission in two years (2004 and 2005) obtained from Pan-European domain is 12 Tg (C) y^{-1} with forest contributing 55% to this emission (Karl et al., 2009). Norway spruce (*Picea abies* Karst.), the second most dominant tree species, covers 30% of the total growing stock (2206 million m^3) in Finland (Peltola, 2009). Norway spruce synthesizes oleoresin, a mixture of diterpenes (C_{20}) and monoterpenes (MTs) for protection against insect herbivores and other organisms (Steinbrecher et al., 1997). Monoterpenes dominate BVOC emissions from non-isoprene emitting coniferous trees (Geron et al., 2000), and contribute 10% to global MT emissions (Guenther et al., 1995), while the emission of sesquiterpenes (SQTs) is relatively low. Conifer trunks are attacked by a wide range of organisms including insects, vertebrates, fungi and bacteria as phloem under the bark is rich in organic nutrients (Franceschi et al., 2005). Conifer trees defend against attacks by bark beetles by resin flow which mostly releases MTs into the atmosphere during polymerization resulting in the formation of protective solid plug (Eller et al., 2013). For example, lodgepole pine trees attacked by *D. ponderosae* are known to increase bark emissions of MT up to 4-fold (Berg et al., 2013) and total BVOC emissions by a 5-to 20-fold (Amin et al., 2012). Engelmann spruce trees attacked by bark beetles increase bark emissions of MT by 3-fold (Berg et al., 2013) and total BVOC emissions by 9-fold (Amin et al., 2013). Likewise, *H. abietis*-damage to young Norway spruce bark increased systemic needle BVOC emissions 5-fold and doubled bark emissions (Blande et al., 2009), while the weevil damage on Scots pine (*Pinus sylvestris* L.) seedlings triggered 4-to 7-fold increase in bark emissions and nearly 3-fold increase in needle BVOC emissions (Heijari et al., 2011).

Climate warming promotes early swarming and multi-voltinism of bark beetles by reducing the length of overwintering period in soil (Jönsson et al., 2009). Climate extremes such as increased intensity of storms and periods with low precipitation result to stressed, weakened, and recently wind-thrown trees which are good reproduction sites for bark beetles (Gitau et al., 2013). For example, disastrous storms in 1990s and 2000s resulted in extensive outbreaks of European spruce bark beetle (*I. typographus* L. Coleoptera: Curculionidae) in central and northern Europe (Wermelinger, 2004; Komonen et al., 2010). The mean mortality rate of Norway spruce typically peaks in the second or third summer following the storm disturbance due to bark beetle dispersal to uninfested stands (Schroeder and Lindelöw, 2002). *Ips typographus* outbreaks with two generations annually occur in southern and south-eastern parts of Finland since the exceptionally warm summer and summer storms in 2010 (P. Lyytikäinen-Saarenmaa, personal observation).

Ips typographus is an aggressive beetle species and the most severe pest of Norway spruce throughout Europe. The attack rates have been found to respond positively to increased summer temperature (Chinellato et al., 2014). Early symptoms of attacks by adult bark beetles are entrance holes (approximately 2–3 mm in diameter), resin flow and brownish frass in spruce bark crevices and trunks. Larval feeding in the bark and phloem leads to disrupted moisture balance in trees, followed by yellowish and then reddish-brown foliage. Larvae feed under thick bark of weakened or dying spruce trees, but adults can attack healthy hosts during the peak phase of an outbreak. Depending on the latitude, numerous round exit holes by the first generation young adults appear from late June to August (Öhrn et al., 2014).

Since mature Norway spruce forests are under the threat of expanding bark beetle attacks, we selected two Norway spruce forest sites (Iitti and Lahti) attacked by *I. typographus* and one unattacked forest site at Kuopio as control for the assessment of *I. typographus* outbreak effects on bark BVOC emissions. Our goal was to determine if (1) attack and feeding damage by bark beetles in the authentic attack site increases the emission rates of BVOCs from Norway spruce bark and if (2) the emission rate is correlated with mean beetle attack density or mean trap catch on study plots, since these are often used as indicators of bark beetle attack intensity. Some soil growing and epiphytic lichen species can be the sources and sinks of volatile and semi-volatile organic compounds (Kesselmeier et al., 1999; Schrlau et al., 2011). Epiphytic lichens (mainly *Hypogymnia physodes* L., Nyl.) and algal cover are commonly found on the bark surfaces of most spruce trees. Therefore, we also wanted to know if lichen and algal cover of the VOC sampling area contributes to BVOC emission rates from the bark surfaces. This study will help to estimate the impacts of bark beetle outbreak on the atmospheric BVOC budget in the disturbed areas.

2. Materials and methods

2.1. Study sites

A Norway spruce stand attacked by *I. typographus* was located at Haapa-Kimola of Iitti municipality (site 1) in southern Finland