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Effects of soil rewetting and thawing on soil gas fluxes: a review of current literature and suggestions for future research

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Abstract

The rewetting of dry soils and the thawing of frozen soils are short-term, transitional phenomena in terms of hydrology and the thermodynamics of soil systems. The impact of these short-term phenomena on larger scale ecosystem fluxes has only recently been fully appreciated, and a growing number of studies show that these events affect various biogeochemical processes including fluxes of soil gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ammonia (NH_3) and nitric oxide (NO). Global climate models predict that future climatic change is likely to alter the frequency and intensity of drying-rewetting events and thawing of frozen soils, highlighting the importance of understanding how rewetting and thawing will influence soil gas fluxes. Here we summarize findings in a new database based on 338 studies conducted from 1956 to 2010, and highlight open research questions. The database revealed conflicting results following rewetting and thawing in various terrestrial ecosystems, ranging from large increases in gas fluxes to non-significant changes. An analysis of published field studies ($n = 142$) showed that after rewetting or thawing, CO_2, CH_4, N_2O, NO and NH_3 fluxes increase from pre-event fluxes following a power function, with no significant differenced among gases. We discuss possible mechanisms and controls that regulate flux responses, and note that a high temporal resolution of flux measurements is critical to capture rapid changes in gas fluxes after these soil perturbations. Finally, we propose that future studies should investigate the interactions between biological (i.e. microbial community and gas production) and physical (i.e. flux, diffusion, dissolution) changes in soil gas fluxes, and explore synergistic experimental and modelling approaches.

1 Introduction

The rewetting of dry soils, or the thawing of frozen soils, represents an abrupt step change in soil biophysical conditions, with implications for biogeochemical cycling.

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From an organismal perspective, soil rewetting and thawing have similar effects because both processes increase the availability of soil water, rehydrate cells, and mobilize nutrients. Both processes are also relatively transient, and the duration of individual rewetting and thawing events varies as a result of the effects of local climatic conditions, topography, drainage, vegetation type, and soil thermal properties (Balser and Firestone, 2005; Vargas et al., 2010b). The sudden flush of water and nutrients that occurs after rewetting and thawing precipitates major changes in plant and microbial activity, with organisms shifting rapidly from dormant or senescent states to active ones (Kieft et al., 1987; Schimel and Clein, 1996; Kemmitt et al., 2008).

It is important to understand the change in fluxes of soil gases (i.e. CO_2, CH_4, N_2O, NO and NH_3) following rewetting and thawing events, as these soil gases are either by-products, intermediates, or end-products of soil-related microbial processes involved in C and N dynamics in soils. These gases also play crucial roles in atmospheric chemistry and CO_2, CH_4 and N_2O gases are greenhouse gases (GHG). Furthermore, future climatic change is likely to alter the frequency and intensity of drying-rewetting events and thawing of frozen soils (Meehl et al., 2006; Sheffield and Wood, 2008; Sinha and Cherkauer, 2010). The frequency and intensity of soil frost (i.e. annual soil freezing days and freeze-thaw cycles) are also likely to be modified since warming could lead to a reduction in the thickness of the insulating snowpack and thus colder winter soil temperatures (Henry, 2008; Gu et al., 2008). It is important to understand how soil rewetting and thawing influences soil GHG fluxes, because increases or decreases in these fluxes may contribute to either positive or negative feedbacks to climate change.

While abrupt increases in soil CO_2, N_2O, NH_3 and NO fluxes following rewetting are commonly observed in various agricultural lands and natural lands (Priemé and Christensen, 2001; Saetre and Stark, 2005), rewetting can either increase (Moore, 1998; Knorr et al., 2008) or inhibit (Kessavalou et al., 1998; Teh et al., 2005) CH_4 oxidation. Similarly, increases in CO_2, CH_4 and N_2O fluxes following soil thawing have been shown to affect total annual gas budgets (Röver et al., 1998; Papen and Butterbach-Bahl, 1999). Despite this growing number of studies, there are still uncertainties in

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our understanding of the mechanisms and impacts on annual gas budgets. These uncertainties are exacerbated by the coarse temporal sampling resolution in most flux measurements that do not capture the dynamics of the pulse (Groffman et al., 2006; Muhr et al., 2009), and by unrealistic simulations of dry-wet and freeze-thaw events (Henry, 2007; Jentsch et al., 2007). These limitations are important for our understanding of soil GHG fluxes because even single pulse events have been shown to contribute substantially to annual fluxes (Lee et al., 2004; Xu et al., 2004).

The growing number of studies on the separate effects of rewetting and thawing specifically on CO_2 and N_2O fluxes have been the focus of several reviews (Henry, 2007; Matzner and Borken, 2008; Borken and Matzner, 2009; Groffman et al., 2009). This review is novel in that it takes a comprehensive approach in dealing with the effect of both rewetting and thawing on multiple soil gas fluxes (CO_2, CH_4, N_2O, NO and NH_3), creates a new database on published studies, and identifies knowledge gaps and current research challenges. Our objectives were to: (1) summarize the effects of rewetting and thawing on multiple soil gas fluxes (CO_2, CH_4, N_2O, NO and NH_3) and highlight common patterns across studies; (2) discuss the underlying mechanisms and drivers of responses; (3) identify knowledge gaps and highlight future research questions.

2 Methodology

2.1 Data collection

Data on changes in gas fluxes of CO_2, CH_4, N_2O, NO and NH_3 following rewetting and thawing were acquired by searching existing refereed literature published between 1950 and 2010 using Web of Science and Google Scholar with search terms such as "rewetting", "thawing", "peak flux", "peak emission" and name of gases. Field observations of rewetting of dry soils include events caused by natural rainfall, simulated rainfall in natural ecosystems, and irrigation in agricultural lands. Similarly, thawing of frozen

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soils include field observations of natural thawing, simulated freezing-thawing events (i.e. thawing of simulated frozen soil by snow removal), and thawing of seasonal ice in temperate and high latitude regions. We included both field and laboratory studies, but did not include the longer term effects of changing active layer depths in this review, as changes in gas fluxes in response to permafrost thaw are affected by both changing soil and plant successional processes (Turetsky et al., 2007). The resulting data set comprised 222 field and laboratory observations focused on rewetting of dry soils, and 116 field laboratory observations focused on thawing of frozen soils.

2.2 Determining individual gas flux change rates and overall change

For studies that reported temporal changes in gas flux rates pre- and post rewetting or thawing events in a single treatment (Fig. 1a), we calculated the change in gas flux rates (%) using the flux values observed before the event (i.e. rewetting or thawing) along with peak flux values that occurred post-event:

$$\text{Flux change} = \frac{(\text{Peak flux}_{\text{post-event}}) - (\text{Flux}_{\text{pre-event}})}{(\text{Flux}_{\text{pre-event}})} \times 100\,\% \tag{1}$$

where Flux change (%) is the relative effect of the event on gas flux, Peak $\text{flux}_{\text{post-event}}$ is the rate of peak gas flux following the event and $\text{Flux}_{\text{pre-event}}$ is the rate of gas flux before the event (i.e. rewetting or thawing). For studies that compared gas fluxes between simulated (representing either rewetting or thawing treatments) and control treatments (Fig. 1b), we calculated changes in gas fluxes exactly as in Eq. (1) but using Peak flux_{Exp} (the rate of peak gas flux following the treatment) and $\text{Flux}_{\text{Control}}$ (the rate of gas flux observed at the control at the time peak gas flux).

Overall, change rates of CO_2, CH_4, N_2O, NO and NH_3 fluxes of pre- and post rewetting and thawing events were determined by fitting linear models to the relationship between $\text{Flux}_{\text{pre-event}}$ and Peak $\text{flux}_{\text{post-event}}$ for both rewetting and thawing events. All analyses were performed using R 2.12.1. (R Development Core Team, 2010). If gas fluxes were presented only in a figure without numeric values reported in text or tables, we calculated the corresponding values from the figure using the software Acrobat 8 Professional ver. 8.2 (Adobe Systems, Inc. San Jose, CA, USA).

3 A review of the effect of rewetting and thawing on soil gas fluxes

For each soil gas we discuss below: (a) how rewetting and thawing events influence gas fluxes in multiple ecosystems and in experimental settings; and (b) the likely mechanisms and environmental controls underlying the observed patterns.

3.1 Carbon dioxide flux from rewetting and thawing

3.1.1 General patterns of responses

Soil surface CO_2 flux (R_S) provides an integrated result of biological CO_2production throughout the soil column, changes in soil CO_2 diffusivity in the soil profile, and in some areas geological processes. Soil CO_2 is produced primarily by both heterotrophic (i.e. decomposer organisms) and autotrophic activity (i.e. living roots and mycorrhizae) (Raich and Schlesinger, 1992; Schlesinger and Andrews, 2000).

Increases in R_S following rewetting of dry soils have been reported in multiple terrestrial ecosystems and various land-use types, including pulses observed in cropland (Kessavalou et al., 1998), grazing pasture (Xu and Baldocchi, 2004), forest (Kim et al., 2010b), grassland (Joos et al., 2010), savannas (Castaldi et al., 2010), and desert (Sponseller and Fisher, 2008). Incubation experiments have yielded similar patterns, showing R_S increases in soils from cropland (Beare et al., 2009), grazing pasture (Wu et al., 2010b), forest (Fierer and Schimel, 2003), grassland (Xiang et al., 2008), peatland (Goldhammer and Blodau, 2008) and desert (Sponseller and Fisher, 2008) ecosystems. For example, in an upper Sonoran Desert ecosystem, R_S increased up to 30-fold immediately following experimental rewetting, and within 48 h returned to the rate of gas flux before the event (Sponseller, 2007). In soil moisture manipulations in

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a Norway spruce plantation, drought and rewetting treatments increased the annual CO_2 flux by 51 % compared with a control plot (Borken et al., 1999). Lee et al. (2004) estimated that the increase in R_S in a single intensive storm amounted to a loss of 0.18 t C ha^{-1} to the atmosphere, or 5–10 % of the annual net ecosystem production in a mid-latitude forest. These studies have reported responses ranging from short-term (ca. 6–24 h) up to 30 d responses (Table 1, Fig. 4), and relative R_S changes ranging from 40 % to >10 000 % increases (Table 1, Fig. 2). Together, these studies support the hypothesis that rewetting a variety of soil types can have substantial effects on the C balance of terrestrial ecosystems (Borken et al., 1999; Lee et al., 2004; Xu et al., 2004). However, we caution that most of these studies lack the high temporal sampling resolution necessary to capture the full dynamic of the pulse (Groffman et al., 2006; Muhr et al., 2009; Vargas et al., 2011).

Increased R_S after thawing has been observed in various terrestrial ecosystems including forest (Wu et al., 2010a), alpine tundra (Brooks et al., 1997), and arctic heath (Elberling and Brandt, 2003), and in incubation experiments with soils from cropland (Kurganova et al., 2007), grassland (Wu et al., 2010b), forest (Goldberg et al., 2008), bog (Panikov and Dedysh, 2000), taiga and tundra (Schimel and Clein, 1996), and Antarctica (Zhu et al., 2009). Reported CO_2 flux increases after thawing can range up to 5000 % (Table 1, Fig. 2). Such increases in CO_2 flux after seasonal thawing were important to the annual budget of CO_2 flux in arable soils (Priemé and Christensen, 2001; Kurganova et al., 2007), but did not affect the annual budget in some natural sites (Coxson and Parkinson, 1987; Schimel and Clein, 1996; Neilsen et al., 2001).

It is important to recognize that R_S could be suppressed during or after rainfall as previous studies have reported: (1) large (10-fold) decreases during light rainfall in arable soils (Rochette et al., 1991), and (2) sharp R_S decreases in no-tillage agricultural fields (Ball et al., 1999). Possible explanations for these reduced R_S rates are: (1) increased water in the soil pore space reduce soil CO_2 diffusivity rates (Rochette et al., 1991; Šimnek and Suarez, 1993), and (2) the restriction of the soil macro-porosity by the rainfall reduces soil air-filled pore space enhances anaerobiosis and reduces aerobic

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respiration (Linn and Doran, 1984; Ball et al., 1999; Davidson et al., 2000). Similar to the rewetting of soils, CO_2 diffusion and production could be affected by an increase of water in the soil pore space after thawing, creating anaerobic conditions that lower autotrophic and heterotrophic respiration. In the following sections we focus on the positive impact of rewetting and thawing on R_S.

3.1.2 Mechanisms and drivers

Two broad mechanisms responsible for increased R_S following rewetting and thawing have been commonly hypothesised: (1) enhanced substrate supply, and (2) changes in physical protection of organic matter. First, microbial metabolism can be enhanced by the availability of accumulated substrates during soil drying periods. A large proportion of microorganisms, fine roots and mycorrhiza die during drought and frozen conditions (Clein and Schimel, 1994; Teepe et al., 2001; Wolf et al., 2010 supplementary information); these dead cells tend to have low C:N ratios and could rapidly decompose during rewetting (Kieft et al., 1987; Van Gestel et al., 1993) and thawing (Priemé and Christensen, 2001; Yergeau and Kowalchuk, 2008). Microorganisms accumulate high concentration of solutes (osmolytes) to retain water inside the cell during drought conditions (Harris, 1981), which rapidly decompose on rewetting (Fiere and Schimel, 2003; Schimel et al., 2007). Furthermore, root exudates from reviving plants following rewetting could significantly affect soil surface flux (Crow and Wieder, 2005; Curiel Yuste et al., 2007). Second, rewetting and thawing could disrupt soil aggregates, exposing physically protected organic matter and increase the accessibility of substrate that can be rapidly mineralized (Groffman and Tiedje, 1988; Appel, 1998; Pesaro et al., 2003; Grogan et al., 2004). Other physical mechanisms that can influence gas flux include infiltration, reduced diffusivity, and gas displacement in the soil (Jensen et al., 1996; Huxman et al., 2004). For example, the infiltration of rainwater may displace CO_2 that accumulates in soil pore spaces during dry periods (Huxman et al., 2004).

The relative contribution of autotrophic or heterotrophic activity to changes in CO_2 fluxes following rewetting and thawing is still poorly understood. In a Mediterranean

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dehesa, autotrophic activity was dominant during drought periods but heterotrophic activity became dominant in CO_2 fluxes following rewetting (Casals et al., 2011).

The magnitude of R_S increases following rewetting may depend on: (1) the size of the soil organic pool; (2) the quality of organic matter, determined by its age, origin, and the extent to which these substrates are protected from microbial attack by adsorption to clay surfaces and inclusion in micro-aggregates; and (3) the properties of soil biota (Van Gestel et al., 1993). Soil moisture conditions before rewetting also influence the response (Orchard and Cook, 1983; Cable et al., 2008), as can the length and severity of drought periods (Unger et al., 2010), and rain pulse size (Sponseller, 2007; Chen et al., 2009). Based on our literature review, we identified the existence of a threshold in soil moisture at 12–20 % gravimetric moisture content, below which a substantial increase in R_S after rewetting is typically observed (Davidson et al., 1998; Xu and Qi, 2001; Rey et al., 2002; Yuste et al., 2003; Dilustro et al., 2005; Cable et al., 2008; Chou et al., 2008; Kim et al., 2010b; Misson et al., 2010; Rewetting, thawing and soil gas fluxes database in Sect. 6. The effects of rewetting may decline with successive drying and rewetting cycles, possibly as a result of a limited pool of labile substrates that have built up over time or during the dry season (Schimel and Mikan, 2005; Goldberg et al., 2008). Importantly, Fernández et al. (2006) suggested that substrate availability, rather than soil moisture, influenced the duration of the CO_2 pulse in response to rain events, while Vargas et al. (2010b) noted that R_S pulses may be driven not only by labile substrate availability, but also by plant photosynthesis rates following the rain event. In addition, management practice (mowing or tillage) (Steenwerth et al., 2010), vegetation type (Shi et al., 2011) and high soil temperatures (Jager and Bruins, 1975; Borken et al., 1999) could influence the magnitude of the response of soil CO_2 flux following rewetting of dry soils.

Studies show that the magnitude of increased R_S following thawing is controlled by characteristics of thawing events. For example, colder temperatures have been shown to increase R_S (Matzner and Borken, 2008; Goldberg et al., 2008). Another known factor is freeze-thaw cycle frequency, where the largest R_S increase commonly occurs

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in the first thawing event (among repeated freezing–thawing cycles) with the effects declining in following cycles (Kurganova and Tipe, 2003; Goldberg et al., 2008).

3.2 Methane flux from rewetting and thawing

3.2.1 General patterns of responses

Net CH_4 flux is the result of the balance between methanogenesis (microbial production under anaerobic conditions) and methanotrophy (microbial consumption) (Dutaur and Verchot, 2007). Methanogenesis occurs via the anaerobic degradation of organic matter by methanogenic archaea within the archaeal phylum *Euryarchaeota* (Thauer, 1988). Methanotrophy occurs by methanotrophs metabolizing CH_4 as their source of carbon and energy (Hanson and Hanson, 1996). In anoxic soils, emergent vegetation also influences CH_4 flux to the atmosphere, as plants enable oxygen transport to the rhizosphere, through aerenchymateous tissue, and through the production of labile substrates via root exudation (Joabsson et al., 1999).

The reported effects of rewetting on CH_4 fluxes are variable. Rewetting reduced CH_4 consumption or increased CH_4 production in arable land (Syamsul Arif et al., 1996; Kessavalou et al., 1998; Hergoualc'h et al., 2008), peatland (Kettunen et al., 1996; Blodau and Moore, 2003; Dinsmore et al., 2009) and tropical forest (Silver et al., 1999). In a wheat-fallow cropping system, CH_4 consumption declined by about 60 % for 3–14 d after rewetting (Kessavalou et al., 1998). In peatland, a pulse of CH_4 was observed after water table drawdown (Moore and Knowles, 1990; Shurpali et al., 1993), and substantial pulses of CH_4 fluxes were produced with both drainage (700 $\mu g\,m^{-2}\,h^{-1}$ above the pre-change mean) and rewetting (over 160 $\mu g\,m^{-2}\,h^{-1}$ above the value of prior to rewetting) within 1–2 days in a mesocosm study (Dinsmore et al., 2009). In contrast, other studies have reported that rewetting increased CH_4 consumption, or reduced CH_4 production, both in the field (Davidson et al., 2004, 2008; Borken et al., 2006; Fiedler et al., 2008) and laboratory (Czepiel et al., 1995; West and Schmidt, 1998). In incubation experiments with alpine soil, CH_4 oxidation increased significantly

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from 11 pmol CH_4 (g dry weight)$^{-1}$ h^{-1} to −67.0 – −29.5 pmol CH_4 (g dry weight)$^{-1}$ h^{-1} 9 days after rewetting (West and Schmidt, 1998). Enhanced CH_4 oxidation was promoted after rewetting for days to weeks in peatland (Öquist and Sundh, 1998; Kettunen et al., 1999; Goldhammer and Blodau, 2008) and rice field (Ratering and Conrad, 1998). However, in an in situ water table drawdown experiment, CH_4 production declined in hummocks but stayed constant in hollows relative to control plots, suggesting a strong role of plant-mediated release of CH_4 in some peatland microforms (Strack and Waddington, 2007).

Similar to the rewetting of soils, the reported effects of thawing on CH_4 fluxes are variable. Seasonal soil thaw increased CH_4 flux in peatland (Tokida et al., 2007), forest (Kim and Tanaka, 2003), and wetlands (Friborg et al., 1997; Song et al., 2006; Ding and Cai, 2007; Yu et al., 2007). In a subarctic peatland, CH_4 flux increased from 2.6 mg m^{-2} d^{-1} to 22.5 mg m^{-2} d^{-1} during thawing, with the latter rate equivalent to approximately 25 % of the mid-summer flux (Friborg et al., 1997). A few studies have also shown enhanced CH_4 consumption during seasonal thawing periods (Ding and Cai, 2007; Wu et al., 2010b). In addition to affecting rates of CH_4 production and oxidation, seasonal soil thaw also may affect CH_4 transport mechanisms (Friborg et al., 1997; Kim and Tanaka, 2003; Tokida et al., 2007). For example, surface seasonal thawing in a bog appeared to trigger ebullition events, with flux up to 25.3 mg CH_4 m^{-2} h^{-1}(Tokida et al., 2007). In Alaskan boreal forest soils damaged by fire, CH_4 flux increased 7–142 % during seasonal thawing (Kim and Tanaka, 2003). While beyond the scope of this paper, we note that as with seasonal thaw, longer term increases in an active layer depth with permafrost thaw also tend to increase CH_4 flux in high latitude wetlands and lakes (Turetsky et al., 2002; Christensen et al., 2004; Walter et al., 2006; Anisimov, 2007). In summary, studies report a large uncertainty in CH_4 responses after rewetting and thawing, and there are much smaller responses in magnitude but fewer observations compared with other gases (Table 1, Fig. 2).

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3.2.2 Mechanisms and drivers

In general, CH_4 production rates are controlled by the availability of suitable substrates, alternative electron acceptors for competing redox reactions (i.e. sulfate reduction), the nutritional status of the ecosystem (i.e. bog versus fen), water table position or soil moisture content, temperature, and soil salinity (Thauer, 1988; Hanson and Hanson, 1996; Dutaur and Verchot, 2007).

The mechanisms and drivers underlying changes in CH_4 flux following rewetting and thawing are complex because they involve the response of both methanogenesis and methanotrophy to changes in availability of substrates, soil environment, particularly soil moisture, and availability of electron donors and acceptors that determine the redox status of soil. Rewetting can increase the availability of water-soluble C substrates (Zsolnay and Görlitz, 1994; Stark and Firestone, 1995) that are being used by soil methanotrophs (Whittenbury et al., 1970). In unfrozen soils, there was no correlation between soil temperature and CH_4 consumption, suggesting strong substrate limitation on methanotrophs (Borken et al., 2006). Borken et al. (2006) also found that methanotrophs were stressed when water contents were below 0.15 g cm^{-3} (in the A horizon), thus rewetting could alleviate osmotic stress and promote the growth and activity of soil methanotrophs (Schnell and King, 1996; West and Schmidt, 1998). While several studies have shown that experimental drought increased CH_4 consumption rates (cf. Borken et al., 2006; Davidson et al., 2008), Fiedler et al. (2008) found no evidence of increased methanotrophy in response to natural drought in forest soils. Methanotrophs responded quickly to water table manipulations in peat soil (Blodau and Moore, 2003). Rewetting also can inhibit methanotrophic activity in more poorly drained soils, for example, if oxygen diffusion becomes limiting (Striegl, 1993). Because methanogenesis requires anaerobic soil conditions, drought typically suppresses CH_4 production, while rewetting increases it. Methanogenic populations require some time to reestablish after rewetting (Fetzer et al., 1993).

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In addition to environmental controls, both methanotrophy and methanogenesis are sensitive to interactions and competition with other microbial redox processes. Drying and rewetting of soils can increase SO_4 pools through remineralization of organic sulfate and/or reoxidation of iron sulfides. This can stimulate sulfate reduction and effectively suppress methanogenesis (cf. Blodau and Moore, 2003). In thick organic soils, this is more likely to occur in surface layers that experience fluctuating water tables than in more saturated, deeper peat layers (Goldhammer and Blodau, 2008).

Freezing increases substrate availability (Sect. 3.1) and limits diffusive transport of gases (including O_2) into and out soil, which could promote methanogenesis and the storage of CH_4 in deeper soil layers (Yu et al., 2007). Also CH_4 typically accumulates subsurface in snow or ice covered ecosystems. During thawing periods, the diffusion barriers disappear, and trapped CH_4 is released to the atmosphere (Friborg et al., 1997; Yu et al., 2007). Methane emissions were independent of temperature below freezing point (Friborg et al., 1997; Yu et al., 2007), suggesting that biological activity was not the dominant control on soil CH_4 flux during early soil thaw. However, as the soil active layer becomes thicker, soil CH_4 fluxes will be driven by soil aeration and redox controls on methanotrophy and methanogenesis, as described above for rewetting. In particular, due to poor drainage of melting snow and seasonal ice, thawing can create saturated surface soils in the active layer, which can favour CH_4 production (Thauer, 1988) and suppress methanotrophy. In contrast, Ding and Cai (2007) found that low temperatures reduced microbial activity of some aerobic microbes, and the resulting presence of more O_2 in soil increased methanotrophy and reduced methanogenesis. Overall, to our knowledge the mechanisms and drivers responsible for the various response of CH_4 to rewetting and thawing have not been clearly explored and further research is needed to identify the mechanisms controlling the response after rewetting and thawing at multiple ecosystems.

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3.3 Nitrous oxide flux from rewetting and thawing

3.3.1 General patterns of responses

Three main processes produce N_2O in soils: (1) nitrification, the stepwise oxidation of NH_3 to nitrite (NO_2^-) and to nitrate (NO_3^-) (Kowalchuk and Stephen, 2001); (2) denitrification, the stepwise reduction of NO_3^- to NO_2^-, NO, N_2O and ultimately N_2, where facultative anaerobic bacteria use NO_3^- as an electron acceptor in the respiration of organic material under low oxygen (O_2) conditions (Knowles, 1982); and (3) nitrifier denitrification, which is carried out by autotrophic NH_3-oxidizing bacteria and the pathway whereby NH_3 is oxidized to nitrite NO_2^-, followed by the reduction of NO_2^- to nitric oxide NO, N_2O and molecular nitrogen (N_2) (Wrage et al., 2001).

Field studies have observed increased soil N_2O flux following wetting in cropland (Barton et al., 2008), grazed pasture (Kim et al., 2010a), tropical forest (Butterbach-Bahl et al., 2004), grassland (Hao et al., 1988), savannah (Martin et al., 2003), and fen (Goldberg et al., 2010a). Laboratory incubation experiments with cropland (Beare et al., 2009), forest (Dick et al., 2001), grassland (Yao et al., 2010), and peatland soils (Dinsmore et al., 2009) have yielded similar results of increased N_2O flux after rewetting. In tropical soils in Costa Rica, N_2O flux pulses began within 30 min, peaking no later than 8 h after rewetting, and 25 g N_2O-N ha^{-1} was emitted for three simulated rain events over a 22-day period (control emitted 14 g N_2O-N ha^{-1}), and one episodic N_2O production event driven by one moderate rain accounted for 15–90 % of the total weekly production (Nobre et al., 2001). These studies have observed a short-term (ca., 12 h) up to 15 d N_2O response following rewetting (Table 2), and an increase of N_2O flux up to 80 000 % with respect to the background conditions (Table 2, Fig. 2). Significantly, our dataset reveals that even a single wetting event can affect annual N_2O flux (from 2 % up to 50 %) (Nobre et al., 2001; Barton et al., 2008; Goldberg et al., 2010a).

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Increased soil N_2O flux following thawing has been observed in cropland (Rochette et al., 2010), grassland (Virkajärvi et al., 2010), forest (Maljanen et al., 2010), marsh (Yu et al., 2007), alpine meadow (Hu et al., 2010), and alpine tundra (Brooks et al., 1997). Laboratory incubation experiments showing similar results have been performed with agricultural (Kurganova et al., 2004), grassland (Yao et al., 2010), forest (Goldberg et al., 2008), permafrost (Elberling et al., 2010), and coastal Antarctica soils (Zhu et al., 2009). Episodic N_2O peak fluxes of up to 750 µg N_2O-N m^{-2} h^{-1} (background levels of under 50 µg N_2O-N m^{-2} h^{-1}) were measured after freeze-thaw in arable field (Dörsch et al., 2004). Such increases usually occur when soil temperatures are close to 0 °C (Christensen and Tiedje, 1990; Chen et al., 1995; Müller et al., 2003). Studies examining the thawing effect on N_2O flux have reported 6 to 35 d response following rewetting (Table 2) and N_2O fluxes increase up to 17 000 % (Table 2, Fig. 2). Thaw-induced N_2O fluxes constituted a major component of annual N_2O fluxes from arable field (Regina et al., 2004; Johnson et al., 2010), temperate grassland (Kammann et al., 1998; Müller et al., 2002), steppe (Holst et al., 2008; Wolf et al., 2010), wetland (Yu et al., 2007) and forest ecosystems (Papen and Butterbach-Bahl, 1999; Wu et al., 2010a; Guckland et al., 2010) with contributions exceeding 50 % of the annual budget in some years.

3.3.2 Mechanisms and drivers

The mechanisms responsible for increased N_2O flux following rewetting have been commonly hypothesized as belonging to two categories: (1) enhanced substrate supply, and (2) the physical mechanisms described above (Sect. 3.1.). Similarly, the enhanced substrate supply described above (see Sect. 3.1.) and the physical mechanisms have been hypothesized as responsible for increased N_2O fluxes following thawing. The hypothesized physical mechanisms for increased N_2O fluxes following thawing are: first, anaerobic water-saturated topsoil conditions are created during thawing by reduced drainage of melting ice and snow in the frozen subsoil, and these conditions are known to increase N_2O fluxes (Li et al., 2000; de Bruijn et al., 2009). Second, ice layers prevent N_2O exchange between topsoil and atmosphere and during thawing

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periods, the diffusion barriers disappear, and the trapped N_2O is released into the atmosphere within a few days (Goldberg et al., 2010b; Virkajärvi et al., 2010). Increased N_2O fluxes following thawing may be caused by the combination of these two mechanisms (Koponen et al., 2006; de Bruijn et al., 2009).

The relative contribution of specific microbial processes (e.g. nitrification, denitrification and nitrifier denitrification) to changes in N_2O fluxes following rewetting and thawing is still poorly understood, although several studies have found denitrification to be a major contribution process in N_2O fluxes following rewetting (Groffman and Tiedje, 1988; Priemé and Christensen, 2001) and thawing (Mørkved et al., 2006; Sharma et al., 2006; Wagner-Riddle et al., 2008).

The magnitude of increased N_2O flux caused by the wetting of dry soils varies depending on the labile N soil pool (Van Gestel et al., 1993; Schaeffer et al., 2003), soil texture (Appel, 1998; Austin et al., 2004), soil water content (Appel, 1998), the size of the rewetting pulse (Ruser et al., 2006; Yanai et al., 2007), length of drought (van Haren et al., 2005), and soil compaction (Uchida et al., 2008; Beare et al., 2009). A significant relationship between the organic N extracted from dried soil samples and the magnitude of N_2O flushes following soil drying-rewetting has been observed (Appel, 1998). Field and laboratory studies with arid and semiarid soils, fine-textured soils with higher water-holding capacity and labile C and N pools compared with coarse-textured soils, showed a greater flush of N_2O flux following rewetting (Austin et al., 2004). In an incubation experiment with soils from a potato field, the amount of increase in N_2O flux following rewetting was enhanced with the amount of water added (Ruser et al., 2006). Furthermore, in another experiment with soils from a field compaction trial, the production of N_2O during the first 24 h following rewetting of dry soil was nearly 20 times higher in compacted than in uncompacted soil (Beare et al., 2009).

The magnitude of increased N_2O flux following thawing of frozen soils is influenced by soil texture (Christensen and Christensen, 1991; Lemke et al., 1998), crop species (Kaiser et al., 1998; Johnson et al., 2010), forest type (Teepe and Ludwig, 2004), tillage history (Singurindy et al., 2009), soil water content (Koponen and Martikainen,

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2004; Wolf et al., 2010), the length of the freezing period (Papen and Butterbach-Bahl, 1999; Wagner-Riddle et al., 2007; Dietzel et al., 2011), and the degree of ice formation (Wagner-Riddle et al., 2010). Soils with clay-dominated aggregates are prone to high N_2O flux during thawing periods (van Bochove et al., 2000; Müller et al., 2003). However, there is little information on the subsequent effect of soil water content on N_2O fluxes (Röver et al., 1998; van Bochove et al., 2000). For example, Röver et al. (1998) measured large fluxes of N_2O after freezing in an agricultural soil at 80 % water-filled pore space, while van Bochove et al. (2000) reported that the N_2O fluxes from a clay soil were significantly larger at a volumetric water content of 39 % than at 28 %.

3.4 Nitric oxide flux from rewetting and thawing

3.4.1 General patterns of responses

Nitric oxide can be produced from: (1) nitrification (Kowalchuk and Stephen, 2001); (2) denitrification (Knowles, 1982); and (3) nitrifier denitrification (Wrage et al., 2001) as described in Sect. 3.3. Increases in soil NO flux following rewetting have been reported in various terrestrial ecosystems, including cropland (Guenzi et al., 1994), grazing pasture (Hutchinson and Brams, 1992), forest (Wu et al., 2010a), grassland (Hartley and Schlesinger, 2000), savanna (Martin et al., 2003), and desert (McCalley and Sparks, 2008). Laboratory incubations with grassland soil (Yao et al., 2010), grazing pasture soil (Hutchinson et al., 1993), forest soil (Dick et al., 2006), and desert soil (McCalley and Sparks, 2008) have reported similar results of increased NO flux after rewetting. NO rewetting studies have commonly reported a short-term (ca., 1–3 d) response following rewetting (Table 2), and the rate of increase of NO flux ranged from 40 % to more than 800 000 % (Table 2, Fig. 2). Some studies indicate that even a single rewetting event could substantially affect the annual flux rates of NO (Davidson et al., 1991; Yienger and Levy, 1995; Kitzler et al., 2006), and rewetting events could be important for regional fluxes (Harris et al., 1996; Ghude et al., 2010).

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Increased soil NO fluxes following thawing have been observed only in a field study (Laville et al., 2011) and in a laboratory incubation study (Yao et al., 2010). In a French crop field, NO fluxes following thawing increased up to 10 $ng\,N\,m^{-2}\,s^{-1}$ and decreased to pre-event values within 24 h while the flux average was 1.7 to 2.3 $ng\,N\,m^{-2}\,s^{-1}$ in two years (Laville et al., 2011). Incubation with the soils of steppe, mountain meadow, sand dune, and marshland in Inner Mongolia showed that NO fluxes were 0.5–8.0 $\mu g\,N\,m^{-2}\,h^{-1}$ at $-10\,^{\circ}C$ and they increased to around 30 $\mu g\,N\,m^{-2}\,h^{-1}$ following thawing (at 5 °C) (Yao et al., 2010).

3.4.2 Mechanisms and drivers

The mechanisms responsible for increased NO fluxes following rewetting have been commonly hypothesized as belonging to the two categories: (1) enhanced microbial metabolism by substrate supply and (2) physical mechanisms described above (see Sect. 3.1.). Several studies found that nitrification is the dominant source of increased NO flux following wetting of dry soils (Davidson, 1992a; Davidson et al., 1993; Hutchinson et al., 1993). The magnitude of increased NO flux can be influenced by the duration and severity of antecedent dry periods (Butterbach-Bahl et al., 2004; McCalley and Sparks, 2008), change in soil moisture (Yienger and Levy, 1995) and temperature (Smart et al., 1999; McCalley and Sparks, 2008), vegetation type (Barger et al., 2005; McCalley and Sparks, 2008), soil type (Martin et al., 2003), microbial demand for N (Stark et al., 2002), frequency of wetting events (Davidson et al., 1991; Hartley and Schlesinger, 2000), previous disturbances (Levine et al., 1988; Poth et al., 1995), and agricultural management (Hutchinson and Brams, 1992). Interestingly, there are conflicting results on the magnitude of increased NO flux after rewetting, which were independent of both the size of rewetting pulse (Davidson, 1992b; Martin et al., 1998) and the periods of antecedent dry days (Martin et al., 1998). Also, other reports have suggested that lower amounts of water addition result in higher NO pulses (Hutchinson et al., 1997; Dick et al., 2001). These conflicting results emphasize the uncertainty and limitations of predicting the magnitude of NO flux responses to soil rewetting. There

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is limited literature on NO flux after thawing, and further research is needed to identify the mechanisms controlling the response after thawing at multiple ecosystems.

3.5 Ammonia flux from rewetting and thawing

3.5.1 General patterns of responses

Soil NH_3 is primarily produced when ammonium ions (NH_4^+) dissociate into gaseous NH_3 under alkaline conditions, and NH_3 flux is sensitive to soil conditions that influence NH_4^+ concentrations (Schlesinger and Peterjohn, 1991; McCalley and Sparks, 2008). Increases in soil NH_3 flux following rewetting have been observed mainly in deserts (Schlesinger and Peterjohn, 1991; McCalley and Sparks, 2008). In the Chihuahuan Desert, USA, simulated rainfall increased NH_3 fluxes from 15 µg N m^{-2} d^{-1} to 95 µg N m^{-2} d^{-1} within 24 h and the fluxes declined as the soils dried during the next 7 days (Schlesinger and Peterjohn, 1991). Similarly, increased NH_3 fluxes following a natural rainfall were 5–10 times higher than pre-rain fluxes in the Mojave Desert, USA (McCalley and Sparks, 2008). Studies examining how rewetting affects NH_3 flux have commonly reported 7 d response following rewetting (Table 2), with the rate of NH_3 flux increase ranging from 200 % to >1000 % (Table 2, Fig. 2). To our knowledge, increase in soil NH_3 flux following thawing has not been observed.

3.5.2 Mechanisms and drivers

The mechanisms responsible for the response of NH_3 to rewetting have not been explored to our knowledge. It is hypothesized that increase in NH_4^+ caused by enhanced N mineralization following rewetting (Tomoaki Morishita, unpublished data) and rewetting promotes reaction between NH_4^+ and OH^-, without biota (James Raich, unpublished data) result in increased NH_3 flux. The magnitude of increased NH_3 flux following rewetting of dry soils can be influenced by land cover type and soil temperature (Schlesinger and Peterjohn, 1991; McCalley and Sparks, 2008). There is a limited

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literature on NH_3 flux and further research is needed to identify the mechanisms controlling the response after rewetting at multiple ecosystems.

3.6 Overall change of gases fluxes following rewetting and thawing

An analysis of published field studies ($n = 142$) showed that CO_2, CH_4, N_2O, NO and NH_3 fluxes following rewetting and thawing increase from pre-event fluxes following a power function, with no significant difference between these events (thawing versus rewetting) or among gases. Thus, the overall response is represented by the following equation (Fig. 3, Eq. 2).

$$\ln\left(\mathrm{Peakflux}_{\mathrm{post-event}}\right) = 2.08\ (\pm 0.11) + 0.88\ (\pm 0.03) \ln\left(\mathrm{Flux}_{\mathrm{pre-event}}\right),$$

$$R^2 = 0.90, N = 142$$

$$\mathrm{Peakflux}_{\mathrm{post-event}} = 8.0(\pm 1.1) \times \mathrm{Flux}_{\mathrm{pre-event}}^{0.88(\pm 0.03)} \tag{2}$$

Similarly, laboratory studies ($n = 10$) showed that CO_2 and N_2O fluxes following rewetting and thawing increase from pre-event fluxes also following a power function, with no significant difference between these events or gases. Thus, the overall response is represented by the following equation (Fig. 3, Eq. 3).

$$\ln\left(\mathrm{Peakflux}_{\mathrm{post-event}}\right) = 3.06\ (\pm 0.71) + 0.76\ (\pm 0.17) \ln\left(\mathrm{Flux}_{\mathrm{pre-event}}\right),$$

$$R^2 = 0.69, N = 10$$

$$\mathrm{Peakflux}_{\mathrm{post-event}} = 21.3(\pm 2.0) \times \mathrm{Flux}_{\mathrm{pre-event}}^{0.76(\pm 0.17)} \tag{3}$$

4 Knowledge gaps and future directions

4.1 Uncertainties in understanding of the responses

In general, rewetting or thawing are associated with increases in CO_2, N_2O, NO and NH_3 fluxes, substantially affecting seasonal and annual flux budgets. However, some

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studies showed no response or small increased fluxes following rewetting or thawing events that did not substantially affect annual flux rates (Garcia-Montiel et al., 2003; Neill et al., 2005; Muhr and Borken, 2009; Muhr et al., 2010). Some studies showed reduced CO_2 or N_2O fluxes during drying periods, but the abruptly increased fluxes following rewetting did not compensate for the reduced or nil uptake rates during the dry period at the seasonal scale (Borken and Matzner, 2009; Goldberg and Gebauer, 2009; Joos et al., 2010).

Overall, the scientific community lacks a good understanding both of the responses of soil gases following rewetting or thawing and of their impact on annual budgets. First, this is because of the relative few studies on this topic. Second, many studies report the magnitude of peak flux or increased rate of flux following rewetting or thawing, but often do not identify: (1) whether peak fluxes are significantly different from fluxes of pre-drought or pre-frozen periods, (2) the change in soil moisture or soil temperature, (3) the time lag between rewetting or thawing events and peak fluxes, (4) peak flux durations, (5) cumulative emissions in peak fluxes, and (6) their contributions to annual budgets. Efforts to collect such information will contribute to improving our understanding of the response of gas fluxes to rewetting and thawing events.

Changes in the relative proportion of CO_2, CH_4, N_2O, NO and NH_3 (e.g. CO_2/CH_4) emitted following rewetting and thawing compared with that of pre-disturbance conditions are poorly understood. To report these ratios and the change, additional efforts are required to conduct multiple gases measurements. This is important since a good understanding of the variation of the relative proportion will improve our understanding of the impact of rewetting or thawing on annual gas budgets.

The effect of rewetting and thawing on dissolved soil gas has been only rarely studied (Matzner and Borken, 2008). To our knowledge, there is only one study showing indirect evidence of this effect, which found that in spring rainfall after thawing increased concentration of dissolved N_2O in soil solutions in forest (Xu et al., 2009). These result suggests that the increased N_2O following rewetting can be dissolved in the soil solution (Xu et al., 2009). This N_2O in the soil solution can drain to surface or groundwater,

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and be a source of indirect N_2O flux (IPCC, 2006). It is therefore important to understand and quantify the effect of rewetting and thawing on dissolved soil gases.

4.2 Uncertainties in understanding of mechanisms and drivers

Enhanced nutrient supply from soil freezing has been accepted as one of the mechanisms to explain abruptly increased N_2O fluxes. However, Hentschel et al. (2009) found that moderate soil freezing did not affect solute losses of N, DOC, and mineral ions from temperate forest soils, and argued that their results did not support the hypothesis that N_2O peak fluxes are caused by the enhanced nutrient supply from soil freezing (Goldberg et al., 2010b). While it has been argued that N_2O peak flux at spring thaw is mostly produced in the surface layer (Müller et al., 2002; Furon et al., 2008; Wagner-Riddle et al., 2008), Goldberg et al. (2010b) found that released N_2O in soil thawing is due to a slow release of subsoil N_2O and a delayed activation of N_2O reductase in the topsoil after soil frost due to low soil temperatures. The relative importance of source processes responsible for the increased fluxes of CO_2(i.e. autotrophic or heterotrophic activity), NO and N_2O (i.e. nitrification, denitrification or nitrifier denitrification) is poorly understood.

In terms of drivers of the response, we observed conflicting results on the magnitude of increased NO flux after rewetting (see Sect. 3.4). How different vegetation types respond to rewetting and thawing events (Teepe and Ludwig, 2004; Matzner and Borken, 2008; Kim et al., 2010b; Shi et al., 2011) is also unclear. This is important because different vegetation types can have different phenologies and photosynthesis rates (Vargas et al., 2010b), nutrient cycling rates in detritus (Vogt et al., 1986), and soils (Borken and Beese, 2005; Paré et al., 2006). Plant-mediated effects on soil microclimate, such as soil temperature and soil moisture (Raich and Schlesinger, 1992; Aussenac, 2000), and plant mediated effects on root and rhizomorph dynamics (Vargas and Allen, 2008) are also only beginning to be explored. Novel mechanisms and pathways by which plants emit gas have been explored recently (Smart and Bloom, 2001; Pihlatie et al., 2005; Keppler et al., 2006; Aubrey and Teskey, 2009; Gauci et al.,

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2010), but how these pathways respond to rewetting or thawing events has been little studied.

Compared to CO_2 and N_2O fluxes, our understanding of the effect of rewetting and thawing on CH_4, NO and NH_3 fluxes and mechanisms and drivers of the variation is limited, with large uncertainties. We encourage the scientific community to perform experiments and observations to better understand their magnitudes and mechanisms.

4.3 Temporal and spatial resolution

Considering the short response time and short effective period of the pulse in soil gas fluxes, many peak fluxes might have been missed in previous studies, as frequently only a few manual measurements were used (Joos et al., 2010; Maljanen et al., 2010). The lack of temporal sampling resolution may also influence the estimation of annual fluxes. In contrast, substantial rewetting effects have been frequently observed with automated chamber systems (Borken et al., 1999: 4–5 observation per a day), eddy covariance methods (cf. Lee et al., 2004; Kim et al., 2010a) and automated measurements of soil CO_2 profiles (Vargas et al., 2010b). Such continuous flux measurements during and after pulse events will help calculate the temporal dynamics and the total contribution to the cumulative flux and annual flux (Maljanen et al., 2010; Vargas et al., 2010a). When manual chamber methods have to be used, more frequent measurements (Smith and Dobbie, 2001; Parkin, 2008) or measurements coinciding with rewetting or thawing events (Beare et al., 2009; Kim et al., 2010b) should be considered.

Most studies have explored the effects of rewetting and thawing at small spatial scales (i.e. plot level). Thus, a critical issue is how to scale up to the ecosystem, landscape or continental scale. Rewetting and thawing pulses may be patchily distributed in space, and without measurements at multiple spatial and temporal scales (i.e. chambers, eddy covariance, upscaling through remote sensing) it is difficult to evaluate the impacts of these events across regions of the Earth. Although multi-spatial scale sampling is needed, we recognize that there is frequently a cost trade-off between temporal sampling and spatial sampling. However, with improving technologies and the growth

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of continental and global networks (i.e. NEON, ICOS, FLUXNET) multi-temporal and multi-scale experiments will become more common in the near future.

4.4 Experimental settings

To test the effect of rewetting and thawing on soil gas flux, controlled experiments have been frequently conducted both in field and laboratory settings using, for example, rainfall exclusions (Borken et al., 2006; Davidson et al., 2008), snow removal (Groffman et al., 2006; Maljanen et al., 2007), and soil cores incubated in the lab (Panikov, 2000). However, these conditions may not accurately simulate natural conditions (Henry, 2007). Future experiments might: (1) simulate drying-rewetting and freezing-thawing based on historical or projected extreme events, the latter under multiple climate change scenarios (Jentsch et al., 2007); (2) collect soil samples in the appropriate season and include relevant surface factors such as plant litter in the autumn or excess water in the spring (Henry, 2007); and (3) develop new methods for simulating field conditions more closely in the laboratory (Hu et al., 2006). Future studies could benefit from these approaches in combination with high-temporal frequency resolution using automated flux measurements.

An area of significant promise involves combining microbial community analyses (Kim et al., 2008; Smith et al., 2010; Sawicka et al., 2009) and/or stable isotope techniques (Wagner-Riddle et al., 2008; Goldberg et al., 2009; Gaudinski et al., 2009) with flux measurements. Whether performed in the lab or field, such experiments could improve our understanding of rewetting and thawing effect on soil gas fluxes, quantifying the relationship between the control factors and their impact.

4.5 Model improvement

Models are promising tools for evaluating the importance of drying-rewetting and freeze-thaw events (Groffman et al., 2009). Simple linear regressions and empirical models have been developed based on the relationships between environmental

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factors including soil moisture and/or soil temperature and soil gas fluxes (Roelandt et al., 2005; Flechard et al., 2007). Some rely on empirical observations but fail under rewetting or thawing conditions (Borken et al., 2003; Lawrence et al., 2009). We propose that further work in this area will increasingly have to incorporate non-linearities in the flux response and the actual substrate and microbial dynamics occurring (Davidson and Janssens, 2006; Vargas et al., 2011).

Process-based models have been developed with the objective of simulating terrestrial ecosystem C and N biogeochemistry including GHGs (e.g. DAYCENT, Parton et al., 2001; DNDC, Li et al., 1992; *ecosys*, Grant and Pattey, 2003). Most existing process-based models require additional work to improve simulating rewetting and thawing effect on soil gas fluxes (Jarecki et al., 2009; Norman et al., 2008; Kariyapperuma et al., 2011). Groffman et al. (2009) suggested that modelling peak fluxes associated with drying and rewetting events requires: (1) accurate simulation of moisture changes in different soil layers and complex shifts in utilisation of fast- and slow-cycling soil organic matter pools by microbes that take place during these events (Miller et al., 2005), and (2) daily or sub-daily simulations of both physical and biological processes (Kiese et al., 2005). They also suggested that the modelling of freeze-thaw induced N_2O fluxes requires consideration of the increase in easily degradable substrates following freezing, tight coupling of nitrification and denitrification in the water saturated topsoil, and the breakdown of N_2O reductase activity at low temperature (Holtan-Hartwig et al., 2002). Regardless of the specific process under consideration, it is critical to enhance the communication between field scientists and the modelling community, as models can be use to generate hypotheses (de Bruijn et al., 2009) to be tested in the field and lab.

5 A Blog for open discussion and web based open databases

The scientific community is taking advantage of sharing capabilities from the Internet by creating open-access databases (Stehfest and Bouwman, 2006; Bond-Lamberty and Thomson, 2010; Reichman et al., 2011) of both published and unpublished data sets. We have created a "Blog" (web-based discussion) entitled "Rewetting, thawing and soil gas fluxes" (http://rewettingandthawing.blogspot.com/), to provide a place where the scientific community can share and update the fast growing knowledge and data on the study of the effect of rewetting and thawing on CO_2, CH_4, N_2O, NO and NH_3 fluxes. This blog provides two major functions. First, we have uploaded a current version of this review paper section by section as an individual post in the Blog; comments can be left under the separate posts. For instance, anyone can correct a potential error, update, or comment on a section. Second, open-access databases, which can be modified by the users, are linked to the Blog: "Rewetting, thawing and soil gas fluxes database" (https://spreadsheets.google.com/spreadsheet/ccc?key=0AjWu6bR8SA9idHY4Tk5TdDZDMWgtMEJsUVhFOWhKLWc\&hl=en_US). The database contains detailed information in the reported studies on soil gas peak flux following rewetting and thawing such as experiment type (lab or field experiment), location, site type, vegetation, climate, soil properties (soil bulk density, soil C, N and pH), rainfall, variation of soil moisture and soil gas flux by wetting and thawing, peak soil gas flux properties (cumulative flux, peak lag time and duration of pulse), and the corresponding references. The database is hosted in web-based spreadsheets and is easily accessible and modified. Our hope is that researchers can thus easily utilize the database, correct errors, and upload missed data or newly collected data. The authors do not have any relationship with the companies currently being used to host the Blog and databases. Finally, version 1 of this database has been archived at the Oak Ridge National Laboratory Distributed Active Archive Center (http://daac.ornl.gov/; in progress) and is available for reproducing the results presented in this study.

6 Conclusions

Rewetting and thawing events are important short term- transitional phenomena in terms of hydrology and the thermodynamics of soil systems. Through this review and

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the compiled dataset, we identified that major soil gases such as CO_2, CH_4, N_2O, NO and NH_3 are influenced substantially by these events. The mechanisms that control these fluxes during rewetting and thawing events are not fully understood, but are critical for our understanding of C and N dynamics and land-atmosphere gas exchange. Specifically we noted that there is a lack of studies on CH_4, NO and NH_3 fluxes. Future climatic change is likely to alter the frequency and intensity of drying-rewetting events and thawing of frozen soils. Thus, rewetting and thawing events could become more critical for land-atmosphere gas exchange and may be more important to incorporate in biogeochemical models. Advancements in this research field are likely to come from high frequency measurements of gas fluxes, soil microbial analyses, isotope measurements, and stronger collaborations between the process-based modelling community and the experimental scientific community. Finally, we advocate for more open access databases within the larger biogeoscience community that researchers can contribute to, maintain/enhance, and utilize for synthesis activities.

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Table 1. Summary of effects of soil rewetting and thawing on soil gas CO_2 and CH_4 fluxes. F = field observation; L = laboratory experiment.

Gas type	Event	Observed ecosystems	Peak periods (d)*	Change rate (%)*	Mechanism	Driver
CO_2	Rewetting	Croplands, grazing pastures, forests, grasslands, savannas, deserts	F:3 (0.25–30), L:4 (0.7–5.5)	F:140 (42–10880), L:500 (112–3000)	1. Microbial metabolism can be enhanced by the availability of accumulated substrate during soil drying periods. 2. Physical mechanisms involving infiltration, reduced diffusivity and gas displacement in the soil can influence gas flux. 3. Vegetation responses to rewetting can increase CO_2 flux.	Size of soil organic pool, the quality of organic matter, the properties of soil biota, moisture state conditions before rewetting, successive cycles, soil temperature, agricultural management practice
	Thawing	Croplands, grazing pastures, forests, grasslands, alpine tundra, arctic heath, Antarctica	L: 1.5 (1.5–7)	F:203 (158–5227), L:500 (112–3900)	1. Microbial metabolism can be enhanced by the availability of accumulated substrate during soil freezing periods. 2. Thawing could disrupt soil aggregates, exposing physically protected organic matter and increase the accessibility of substrate that can be rapidly mineralized.	Substance availability, frost temperatures, freeze-thaw event frequency
CH_4	Rewetting	arable land, peatland, tropical forest;	F:2 (2–3), L:2 (2–32)	F:76 (60–667), L:−453 (−709–88.5)	1. Wetting increases the availability of water-soluble carbon substrates and soil methanotrophs are able to use this carbon. 2. Water-soluble carbon substrates reduce O_2 concentrations and support soil methanogens which then supply CH_4 to methanotrophs. 3. Drought typically suppresses CH_4 production, while rewetting increases it. Methanogenic populations require some time to re-establish after rewetting 4. Drying and rewetting of soils can increase SO_4 pools through remineralization of organic sulfate and/or reoxidation of iron sulfides. This can stimulate sulfate reduction and effectively suppress methanogenesis. 5. Rewetting inhibits methanotrophic activity in more poorly drained soils.	Not yet revealed
	Thawing	peatlands, forest, mineral wetlands	L:7	F:433 (33–765), L:1100	1. Freezing increases substrate availability and limits O_2 transport into soil, both of which would promote methanogenesis and CH_4 is stored in deeper soil layers. 2. During thawing periods, the diffusion barriers disappear, and trapped CH_4 is released to the atmosphere. 3. Thawing can create saturated surface soils in the active layer, which can favour CH_4 production and suppress methanotrophy. 4. Low temperatures reduced microbial activity of some aerobic microbes, and the resulting presence of more O_2 in soil increased methanotrophy and reduced methanogenesis.	Not yet revealed

*median (min.–max.)

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Table 2. Summary of effects of soil rewetting and thawing on soil gas N_2O, NO and NH_3 fluxes. *F* = field observation; *L* = laboratory experiment.

Gas type	Event	Observed ecosystems	Peak periods (d)*	Change rate (%)*	Mechanism	Driver
N_2O	Rewetting	Croplands, grazing pastures, forests, grasslands, savannas, fen	F:2 (0.5–15), L:4 (3–8)	F:800 (102–83 233), L:4100 (100–439 700)	1. Microbial metabolism can be enhanced by the availability of accumulated substrate during soil drying periods. 2. Physical mechanisms involving infiltration, reduced diffusivity and gas displacement in the soil can influence gas flux.	labile N soil pool, soil texture, soil water content, size of the rewetting pulse, length of drought, soil compaction
	Thawing	Croplands, grazing pastures, forests, grasslands, marsh, alpine tundra	F:35 (6–35), L:6 (2–11)	F:1233 (253–17327), L:1400 (100–100 000)	1. Microbial metabolism can be enhanced by the availability of accumulated substrate during soil freezing periods. 2. Physical mechanisms involving reduced diffusivity can influence N_2O fluxes.	soil texture, crop species, forest type, tillage history, soil water content, the length of the freezing period
NO	Rewetting	Croplands, grazing pastures, forests, grasslands, savannas, deserts	F:1 (1–3), L:4 (0.2–7)	F:856 (43–810 400), L:500 (50–11 500)	1. Microbial metabolism can be enhanced by the availability of accumulated substrate during soil drying periods. 2. Physical mechanisms involving infiltration, reduced diffusivity and gas displacement in the soil can influence gas flux.	duration and severity of antecedent dry periods, size of rewetting pulse??, soil temperature, vegetation type, soil type, microbial demand for N, frequency of wetting events, previous disturbances (i.e. fire), agricultural management type
	Thawing	Cropland, mountain meadow		F:400, L:350 (40–500)	Not yet revealed	Not yet revealed
NH_3	Rewetting	Deserts	F:7 (7–7), L:2 (2–2)	F:489 (200–1067), L:550 (400–800)	Not yet revealed	cover type, soil temperature
	Thawing	Not observed				

*median (min.–max.)

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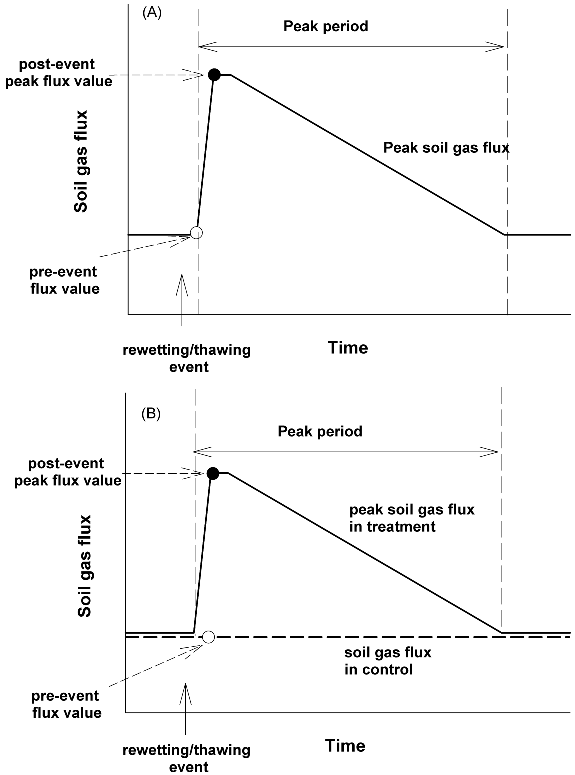

Fig. 1. Hypothetical figures representing peak soil gas flux in rewetting of dry soils and thawing of frozen soils and peak flux period. Peak gas flux occurred in natural rewetting or thawing event (solid line) and pre-event flux value (white dot) and post-event peak flux value (black dot) used to determine flux change rate **(A)**; peak gas flux occurred in rewetting or thawing treatment (solid line) and gas flux in control (dot line) and pre-event flux value (white dot, the flux value in control when post-event peak flux value is read) and post-event flux value (black dot) used to determine flux change rate **(B)**.

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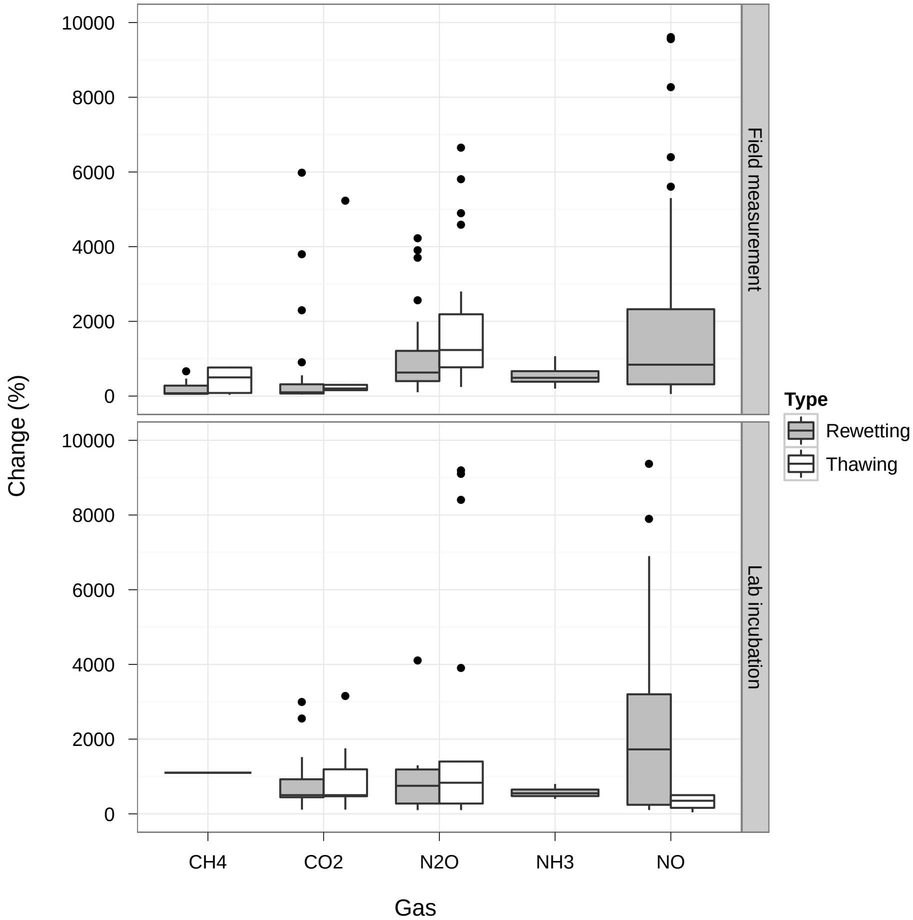

Fig. 2. Change rate (%) of soil gas CO_2, CH_4, N_2O, NO and NH_3 fluxes following soil rewetting and thawing in field and laboratory experiments.

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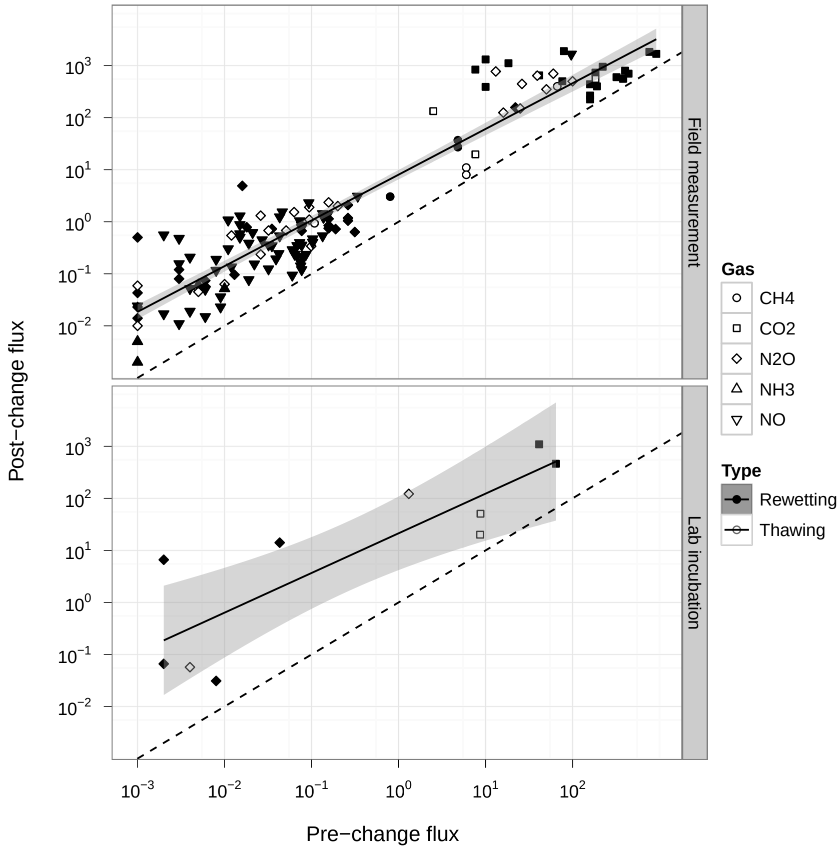

Fig. 3. Relationship between CO_2, CH_4, N_2O, NO and NH_3 fluxes of pre- and post rewetting and thawing events in the field studies and laboratory experiments. Axes units are mg gas m^{-2} h^{-1} (for field measurements) and mg gas kg soil^{-1} h^{-1} (for lab incubations). The dashed lines represent 1:1 relationship.

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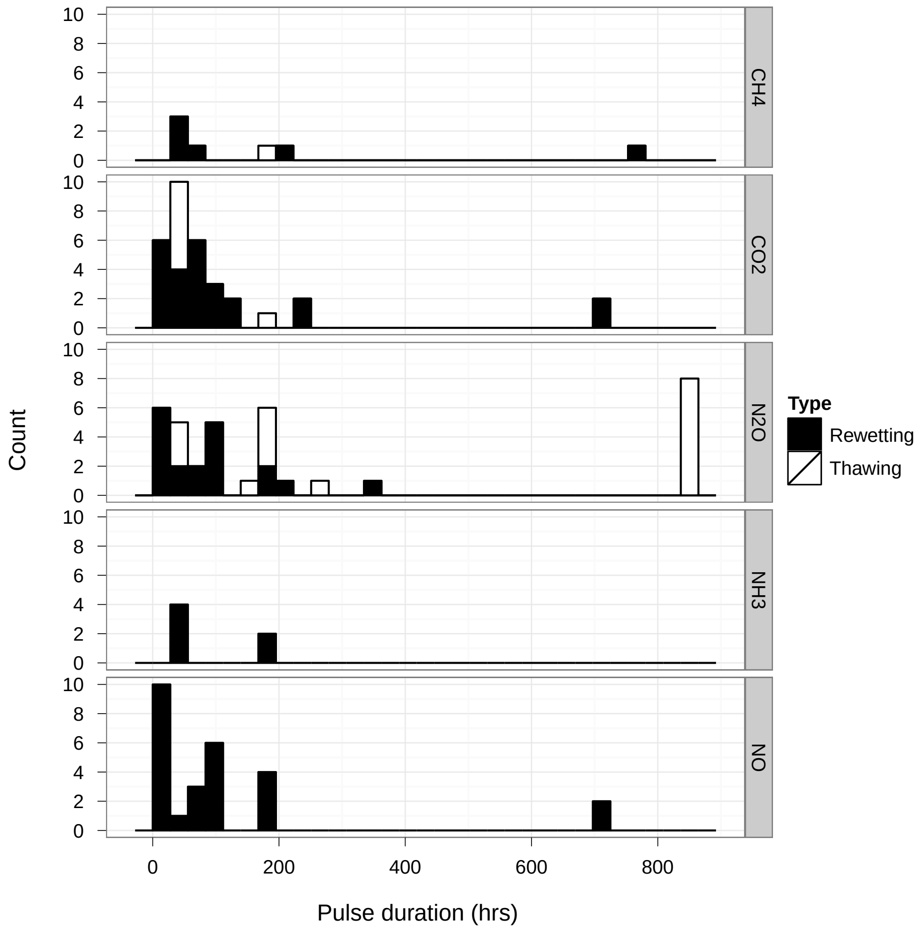

Fig. 4. Histograms of the duration of enhanced flux of soil gas CO_2, CH_4, N_2O, NO and NH_3 fluxes following soil rewetting and thawing in field and laboratory experiments.

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