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Technical note: Methionine, a precursor of methane in living plants

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Abstract

When terrestrial plants were identified as producers of the greenhouse gas methane, much discussion and debate ensued, not only about their contribution to the global methane budget, but also with regard to the validity of the observation itself. Although the phenomenon has now become more accepted for both living and dead plants, the mechanism of methane formation in living plants remains to be elucidated and its precursor compounds identified. We made use of stable isotope techniques to verify in vivo formation of methane and, in order to identify the carbon precursor, ^{13}C-positionally labelled organic compounds were employed. Here we show that the amino acid L-methionine acts as a methane precursor in living plants. Employing ^{13}C-labelled methionine clearly identified the sulphur-bound methyl group of methionine as a carbon precursor of methane released from lavender (*Lavandula angustifolia*). Furthermore, when lavender plants were stressed physically, methane release rates and the stable carbon isotope values of the emitted methane greatly increased.

Our results provide additional support that plants possess a mechanism for methane production and suggest that methionine might play an important role in the formation of methane in living plants, particularly under stress conditions.

1 Introduction

The observation that plants produce methane (CH_4) under aerobic conditions has caused considerable controversy amongst the scientific community (Keppler et al., 2006; Dueck et al., 2007; Evans, 2007; Beerling et al., 2008; Kirschbaum and Walcroft, 2008; McLeod et al., 2008; Vigano et al., 2008; Wang et al., 2008; Nisbet et al., 2009; Bloom et al., 2010; Covey et al., 2012; Zhang et al., 2014). Despite much scepticism a number of recent studies provide support for the phenomenon not only for living plants but also for dead plant matter (Keppler et al., 2009; Qaderi and Reid, 2011; Bruhn et al., 2012; Wang et al., 2013).

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Non-microbial CH_4 release has been shown to occur under ultraviolet (UV) irradiation and elevated temperatures from dry and detached fresh plant material (McLeod et al., 2008; Vigano et al., 2008; Bruhn et al., 2009). Pectin has been considered a precursor of CH_4 primarily because of its high degree of methylation (Keppler et al., 2008; Bruhn et al., 2009; Messenger et al., 2009). A reaction of reactive oxygen species (ROS) with pectic polysaccharides was suggested as a possible route to CH_4 formation under UV radiation (Messenger et al., 2009). From plant matter, CH_4 can be derived from other structural components, such as commercially purified lignin and cellulose (Vigano et al., 2008), leaf surface waxes (Bruhn et al., 2014), and even from ascorbic acid under highly oxidative conditions (Althoff et al., 2010). For further information on CH_4 formation, the reader should refer to the recent reviews of Bruhn et al. (2012) and Wang et al. (2013).

Stable isotope analysis has been employed to demonstrate that living plants release CH_4 at rates ranging from 0.16 to 12 $ng\,g^{-1}$ dry weight (DW) h^{-1} (Brüggemann et al., 2009; Wishkerman et al., 2011). Isotope labelling studies involving young poplars grown in a $^{13}CO_2$ atmosphere (Brüggemann et al., 2009) together with several plant cell culture experiments with ^{13}C-labelled sucrose (Wishkerman et al., 2011) confirmed that CH_4 is produced in plants per se and not by their associated micro-organisms. They suggested that CH_4 formation was the result of abiotic stress factors to which the plant had been exposed, an idea supported by findings of two other recent studies (Qaderi and Reid, 2009, 2011). Although these results would support the contention that living plants release CH_4, the mechanism of its formation and its precursors still remain unknown.

A first step towards delineating the formation pathway was recently undertaken by Wishkerman et al. (2011), who investigated the influence of the toxin sodium azide (NaN_3) on cell cultures such as tobacco, sugar beet and grape vine. As sodium azide is known to disrupt electron transport flow at the cytochrome c oxidase (complex IV) in plant mitochondria, their findings suggest that disturbance of the electron transport chain (ETC) cause CH_4 formation in plant cells. Thus CH_4 formation in living plants

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may be an integral part of cellular responses to changes in oxidative status present in all eukaryotes. It has been hypothesized that compounds such as phosphatidylcholine or methionine (Met) might be carbon precursors of CH_4 in both animal and plant cells, particularly when under stress conditions (Wishkerman et al., 2011; Bruhn et al., 2012).

Furthermore, very recently a chemical reaction showing that CH_4 can be readily formed from organosulfur compounds under oxidative conditions, ambient atmospheric pressure, and temperature has been suggested (Althoff et al., 2014). In the first step of the reaction, methyl sulfides are oxidised to the corresponding sulfoxides. Then, in the next step, demethylation of the sulfoxide via homolytic bond cleavage leads to methyl radical formation and finally to CH_4. In the same study tobacco plants (*Nicotiana tabacum*) grown under sterile conditions were supplemented with positionally labelled Met, where only the methyl group (–S–CH_3) was enriched with ^{13}C atoms. These experiments provided the first evidence that the thio-methyl group of Met is a parent compound of CH_4 in tobacco plants. The potential role of methionine and its oxidation product methionine sulfoxide (MSO) in CH_4 biosynthesis in living plants was also suggested by Bruhn et al. (2012). Additionally, methionine has been shown to be involved in CH_4 formation in saprotrophic fungi (Lenhart et al., 2012).

In this study we investigated methionine, an amino acid that plays a major role in trans methylation reactions, as a precursor of CH_4 biosynthesis in living plants under dark conditions. We employed Lavender (*L. angustifolia*) which was previously shown to produce significant amounts of CH_4 both under normal and stress conditions such as physical wounding and anoxia (Z.-P. Wang et al., 2009, 2011, Z. Wang et al., 2011). We made use of stable isotope techniques and ^{13}C-positionally labelled methionine to verify in vivo formation and identify the carbon atom precursor of CH_4.

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2 Material and methods

2.1 Cultivation of plants

Commercially available lavender plants (*L. angustifolia*) grown to approximately 20–25 cm were purchased for the initial experiment. Plants used in the second experiment were grown in a greenhouse until a height of 20 cm was reached. Trace gas measurements were carried out at 22 ± 2 °C and 100 % humidity under dark conditions.

2.2 Supplementation of lavender plants with ^{13}C-methionine

Lavender plants were removed from pots and the soil was washed from the roots. For incubation, each plant was placed inside a 2.5 L flask (Weck©, Hanau, Germany) containing 50 mL distilled H_2O and then sealed with a lid held in place with a rubber band. To facilitate headspace sampling each lid had a central hole fitted with a silicone stopper. In the ^{13}C-Met labelled flasks the distilled water was supplemented with 0.4 mM ^{13}C-Met. We used a positionally labelled Met where only the methyl group (–S–CH_3) was enriched with ^{13}C atoms. After sealing, measurements of headspace CH_4 concentrations and ^{13}C-CH_4 signatures were conducted over a four day period. Different incubation periods and measurement intervals were necessary to correspond with the available schedule times for use of the isotope measurement system. For isotope measurements the incubation flask was directly connected to the IRMS system.

2.3 Physical stressing of plants

Detached leaves of *L. angustifolia* have previously been shown to release significant amounts of CH_4 both under normal and stress conditions, such as physical wounding by cutting (Z. Wang et al., 2011). However, stressing lavender plants by cutting is a time-consuming process and a rapid, stress-induced increase in CH_4 emissions might occur during this process and before the flasks were sealed. Therefore, physical

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stress in our study was performed by gently compressing individual leaves of each plant between fingertips for a short time period (one to two seconds). This procedure took approximately one minute for each plant ($n = 6$).

2.4 Analytical procedures

Gas samples were analysed within 24 h on a gas chromatograph (Shimadzu GC-14B, Kyoto, Japan) with a flame ionization detector (CH_4) and an electron capture detector (N_2O, CO_2) operated at 230 and 320 °C with N_2 as carrier gas (25 mL min^{-1}) (Kammann et al., 2009, 2012). The GC column (PorapakQ, Fa. Millipore, Schwallbach, mesh 80/100) was 3.2 m long and 1/8 inch in diameter. The length of the precolumn was 0.8 m. The GC gas flow scheme and automated sampling was that of Mosier and Mack (1980) and Loftfield et al. (1997), and peak area integration was undertaken with the Software PeakSimple, version 2.66. The SD of the mean of six atmospheric air standard samples was below 1.0, 0.5, and 0.2 % for CO_2, N_2O, and CH_4, respectively.

2.5 Continuous flow isotope ratio mass spectrometry (IRMS) for measurement of $\delta^{13}C$ values of CH_4

Headspace gas from the flasks was transferred to an evacuated sample loop (40 mL). Interfering compounds were separated by GC and CH_4 trapped on Hayesep D. The sample was then transferred to the IRMS system (ThermoFinnigan Delta^{plus} XL, Thermo Finnigan, Bremen, Germany) via an open split. The reference gas was carbon dioxide of high purity (carbon dioxide 4.5, Messer Griesheim, Frankfurt, Germany) with a known $\delta^{13}C$ value of −23.64 ‰ (V-PDB). All $\delta^{13}C$ values were normalized relative to V-PDB (Vienna Pee Dee Belemnite) using a CH_4 standard. Samples were routinely analysed three times ($n = 3$) and the average SDs of the GC/C/IRMS measurements were in the range of 0.1 to 0.3 ‰.

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All $^{13}C/^{12}C$-isotope ratios are expressed in the conventional δ notation in per mil vs. V-PDB, [‰] using the following equation (Eq. 1):

$$\delta^{13}C_{\text{V-PDB}} = \left(\left(^{13}C/^{12}C\right)_{\text{sample}} / \left(^{13}C/^{12}C\right)_{\text{standard}}\right) - 1. \quad (1)$$

2.6 Statistics

Evaluation of results from experiments with lavender plants utilised the software package SPSS Version 20. In the initial experiment (experiment 1) a paired sample *t* test was used to compare the rates of CH_4 production between consecutive treatments "non-stressed" and "stressed" on the same plants (Levene-Test was 0.394 after log transformation of data). For the purposes of brevity, from this point forward this experiment will be referred to as the consecutive treatment experiment. The second experiment where simultaneously different samples were used to compare between "non-stressed" and "stressed" treatments is referred to as the parallel treatment experiment. The CH_4 and $\delta^{13}CH_4$ emission ratio between stressed and non-stressed plants (Table 1) was calculated by using the mean value of the samples 9–11 as reference for the non-stressed plants.

Data from the parallel treatment experiment (also referred as experiment 2) and differences between experiments 1 and 2 were analysed by an independent samples *t* test. Differences between results are given as significant ($p < 0.05$) or highly significant ($p < 0.001$).

In the case where no significant differences occurred between the control (no stress applied or Met added) and the treatment where only Met was added, CH_4 emission rates and $CH_4 : CO_2$ ratios were pooled in order to calculate the mean values.

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3 Results

3.1 Lavender plants supplemented with –S–CH_3 positionally labelled Met and the effect of physical stress

We investigated CH_4 emissions of *L. angustifolia* supplemented with ^{13}C-positionally labelled Met ($^{13}CH_3$-Met; only the methyl group –S–CH_3 was enriched with ^{13}C atoms) under stressed and non-stressed conditions. The incubations were carried out in total darkness in order to exclude possible light effects and to measure the gross respiration of plants. The effect of physical stress was investigated in parallel experiments, where in each case three different individual plants were placed under "stressed" and "non-stressed" conditions. Additionally, an experiment was performed where CH_4 emissions were first measured on intact plants, and then, after physical stress was applied to these plants, CH_4 emissions were again measured.

The CH_4 emission rates of non-stressed *L. angustifolia* plants ranged from 0.06 to 0.57 ng CH_4 g^{-1} DW h^{-1}, with a mean value of 0.33 ± 0.16 ng CH_4 g^{-1} DW h^{-1} (Table 1). Physical stress enhanced CH_4 emissions by a factor of 5.7 up to a mean CH_4 emission rate of 1.7 ± 0.57 ng g^{-1} h^{-1} ($n = 8$). The effect of physical stress was significant both for plants undergoing consecutive treatment (paired t test with $p = 0.002$, $n = 5$) and those in the parallel treatment experiment (independent samples t test with $p = 0.005$). Addition of Met did not affect the CH_4 production of non-stressed *L. angustifolia* plants (Table 1, comparison of flasks 6–8 vs. 9–11; $p = 0.632$, $n = 3$).

Lavender plants ($n = 2$) supplemented with $^{13}CH_3$-Met showed a strong response in the isotope signal with $\delta^{13}C(CH_4)$. After addition of $^{13}CH_3$-Met to the roots ($n = 2$) $\delta^{13}C(CH_4)$ values increased from −47 at time 0 to 29 and 97 ‰ after 20 h in non-stressed (Fig. 1d) and stressed plants (Fig. 1f), respectively, whereas in the control samples ($n = 3$) only a marginal change (±1 ‰) was noted (Fig. 1b). Mean changes in $\Delta^{13}CH_4$ signature were 0.39 ± 0.16 ‰ g^{-1} h^{-1} for the non-stressed plants. After stressing, a strong response in the mixing ratio of CH_4 occurred (Fig. 1), reaching

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a $\Delta^{13}CH_4$ up to 0.64 ± 0.30 ‰ g^{-1} h^{-1} (Table 1). The ^{13}C signature increase in headspace-CH_4 over time (Fig. 1d and f) clearly shows that the methyl group of Met is a precursor of CH_4 in plants under both non-stressed and stressed conditions.

For non-stressed and stressed plants, on average 0.008 and 0.009 % of $^{13}CH_3$-Met molecules were daily converted to CH_4, assuming that all $^{13}CH_3$-Met was taken up by the plant.

The ratio of CH_4 emissions (5.7) and $\Delta^{13}CH_4$ h^{-1} g^{-1} (1.9) between stressed and non-stressed plants (Table 1) indicated a higher effect of physical stress on CH_4 formation than on the changes in $\delta^{13}C(CH_4)$ values.

3.2 Respiration

During incubation of *L. angustifolia*, changes in the CO_2 mixing ratio were also monitored. Since the incubation was conducted in the dark, no CO_2 uptake took place and thus changes in the mixing ratio only reflect plant respiration. Respiration was on average for non-stressed and stressed plants 0.36 ± 0.14 and 0.50 ± 0.16 mg CO_2 g^{-1} h^{-1}, respectively.

The CO_2 production by respiration reflects metabolic activity of the plants, and to relate CH_4 production to metabolic activity, we related CH_4 formation to respiration by calculating the $CH_4 : CO_2$ ratio [pmol : µmol] separately for each sample. Figure 2 shows the CH_4 and CO_2 production rates and the respective $CH_4 : CO_2$-ratio, which was 2.0 ± 1.1 for the non-stressed plants ($n = 6$) and 8.5 ± 1.8 for the plants where physical stress was applied ($n = 3$). Thus, physical damage resulted in a 5-fold increase in the $CH_4 : CO_2$ ratio ($p = 0.004$). Supplementation of plants with Met did not affect the CH_4 or CO_2 emission rates ($p > 0.1$).

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4 Discussion

4.1 Effects of physical stress on CH_4 production

Methane emission rates of 0.33 ± 0.16 and $1.71 \pm 0.57\,ng\,g^{-1}\,DW\,h^{-1}$ were observed for *L. angustifolia* under non-stressed and physically stressed conditions, respectively. The upper range (under physical stress) here is still considerably lower (one to two orders of magnitude) than the range of CH_4 emission rates from intact living plants (12 to $370\,ng\,g^{-1}\,DW\,h^{-1}$) reported by Keppler et al. (2006) and those reported from crop species under environmental stress (Qaderi and Reid, 2009, 2011).

Without the application of physical stress the calculated emission rates were considerably lower (factor of three) with maximum values reaching $0.57\,ng\,CH_4\,g^{-1}\,DW\,h^{-1}$ and are similar to those reported in previous studies employing stable carbon isotope labelling tools (Bruggemann et al., 2009; Wishkerman et al., 2011). The very low values reported here again highlight the benefit of using stable isotope tools, as it would be very difficult to clearly monitor aerobic CH_4 formation in non-stressed living plants without their employment. This might also include the sensitive optical online methods employed in several studies (Dueck et al., 2007; Beerling et al., 2008). However, these spectroscopic methods might be able to measure CH_4 formation in plants under particular stress conditions.

Earlier studies (Z.-P. Wang et al., 2009, 2011, Z. Wang et al., 2011) already revealed a significant increase of CH_4 emissions after physical injury and suggested reactive oxygen species (ROS) to be involved in the cleavage of methyl groups from pectin and/or lignin (Z. Wang et al., 2011; Keppler et al., 2008; McLeod et al., 2008; Messenger et al., 2009). Our finding of close to a 6-fold increase in CH_4 emissions after application of physical stress is within the range of the values reported by Z. Wang et al. (2011) where the CH_4 emission rates of lavender plants were 0.42 ± 0.05 and $6.32 \pm 0.69\,ng\,g^{-1}\,h^{-1}$ for intact plants and after wounding, respectively. In that study observations of CH_4 emission rates of intact plants ($0.4\,ng\,g^{-1}\,h^{-1}$) and after wounding

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($0.7\,ng\,g^{-1}\,h^{-1}$) for 56 plant species were reported. The discrepancy in the physical stress-induced response in CH_4 emissions of lavender plants might be due to an exceptionally high response of this species when compared to other species tested by Z. Wang et al. (2011). Differences in the stress-response between samples for the lavender plants (ratio between stressed and non-stressed plants beeing in a range of 3.3 to 11.2) in this study might be due to a different degree of injury during the compression of the individual leaves of each plant.

4.2 $CH_4 : CO_2$-ratio

Based on the CH_4 and CO_2 emission rates, the calculated $CH_4 : CO_2$ ratio [pmol : µmol] of intact lavender plants was 2.0 ± 1.1 ($n = 6$), i.e. per mol CO_2 2.0 µmol CH_4 was released by the plants.

This is close to the ratios observed for saprotrophic fungi including *Pleurotus sapidus*, *Stereum sanguinolentum*, *Panaerochaete chrysosporium* where the $CH_4 : CO_2$-ratio was 3.5 ± 1.92 pmol : µmol or 1.15 ± 0.70 ng : mg (Lenhart et al., 2012) and cryptogams including mosses and, lichens ($n = 31$) with a ratio of 2.58 ± 2.60 pmol : µmol or 0.94 ± 0.95 ng : mg (Lenhart et al., 2014). The $CH_4 : CO_2$-ratio of lavender tends to be lower, but, as indicated by the SD, this difference is not significant.

The physical stress-induced increase in the $CH_4 : CO_2$ ratio (factor 5) of up to 8.5 ± 1.8 was caused by a significant increase in CH_4 emissions, accompanied only by a small increase in respiration. The overall stress-induced increase in respiration of lavender plants compared to non-stressed plants was 40 % (n.s., $p > 0.3$), which is similar to the increase observed by Wang et al. (2009), who reported a 50 % increase in CO_2 emissions for plants physically wounded by cutting compared to those left uncut. The $CH_4 : CO_2$-ratio might be a useful tool to relate CH_4 emissions to metabolic activity in the dark and to compare CH_4 emission rates of different species obtained under different conditions.

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4.3 Methionine as a precursor of CH_4 in plants

Based on the addition of $^{13}CH_3$-Met and stable carbon isotope measurements it was possible to clearly monitor $^{13}CH_4$ formation in lavender plants. The increase in the $\delta^{13}CH_4$ signature of CH_4 released by lavender plants after supplementation with $^{13}CH_3$-Met (Fig. 1, Table 1) is a strong indicator that the methyl thiol group of Met is a CH_4 precursor during metabolic processes. When plants were physically stressed, there was not only an increase in CH_4 release but also an increase in its $^{13}CH_4$ signature (Fig. 1, Table 1).

It is important to note that our data cannot be used to conclude that the methionine per se is a direct precursor of CH_4 in plants. Indeed, since most methionine resides in proteins it is much more likely to be the source of CH_4 production after oxidation by ROS, as suggested by Bruhn et al. (2012). They based their hypothesis on the finding that dimethyl sulfoxide (DMSO) could act as a hydroxyl radical scavenger in cells and produces CH_4 via a radical mechanism (Repine et al., 1981). They argued that when the amino acid methionine is oxidized, the first oxidized product is methionine sulfoxide, where the side chain is similar to DMSO. Therefore methionine sulfoxide might also be a precursor of CH_4 biosynthesis. The concentration of the free amino acid in normal plant tissues is $< 100\,\mu M$ (Inaba et al., 1994), while that found in protein is two to three orders of magnitude higher (Bruhn et al., 2012). Methionine residues are known to be prone to oxidation by H_2O_2 (Levine et al., 1996; Moller et al., 2007) to form methionine sulfoxide. Based on the calculations of Bruhn et al. (2012), it would only require a conversion rate and release of less than one CH_4 molecule per hour for every 1000 protein methionine sulfoxide to explain a release rate of $10\,ng\,CH_4\,g^{-1}\,DW\,h^{-1}$ by intact plant tissues. These considerations are strongly supported by findings reported in a recent chemical study (Althoff et al., 2014), which suggest that under oxidative conditions demethylation of sulfoxides might lead to CH_4. In their study methyl groups of organosulfur compounds were shown to be efficiently converted to CH_4 when using iron(II/III), hydrogen peroxide and ascorbic acid as reagents. It is thought that methyl

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sulfides are first oxidised to the corresponding sulfoxides and demethylation of the sulfoxide via homolytic bond cleavage leads to methyl radical formation and then to CH_4.

However, in our study we focused on the identification of the precursor compound of CH_4 in living plants and the location of the carbon atom within the precursor molecule. Thus additional investigations and measurements concerning the formation of ROS, distinguishing between free methionine and that in protein, as well as the possibility of methionine residue oxidation to Met-SO need to be undertaken.

5 Conclusions and outlook

Our study is an important step in deciphering the precursor compounds involved in CH_4 biosynthesis in living plants. The employment of $^{13}CH_3$-Met clearly showed that the sulphur bonded carbon atom of the methyl group in methionine was transferred to CH_4 in lavender plants. Knowledge of the precursor compound and identification of the carbon atom involved is a first step towards elucidating the pathway of its formation. An understanding of the mechanisms of CH_4 formation in living plants may reveal if the process has a more general physiological role. Further experiments where other stress factors in combination with $^{13}CH_3$-methionine are investigated should provide further insight into the pathways involved in CH_4 formation.

Although it has been argued that plants may not produce CH_4 as an end-product or by-product of their metabolism (Nisbet et al., 2009), our results would strongly indicate that plants do contain a mechanism for CH_4 production. The stress-induced increase in CH_4 emissions together with studies on sterile plants (Wishkerman et al., 2011) or cryptogamic covers supplemented with diverse inhibitors (Lenhart et al., 2014), do not support the hypothesis of a noteworthy contribution of Archaea to plant-derived CH_4-formation. However, we did not to scan for methanogenic Archaea in the wooden parts of lavendula plants to exclude Archaeal-derived CH_4 formation as postulated by Covey et al. (2012). Furthermore, it is assumed that organosulfur compounds might play an

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important role in the formation of CH_4 in living plants particularly when under stress conditions.

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Table 1. Rates of formation and $\delta^{13}C$ signature increase of CH_4 released during incubation of *L. angustifolia* plants before and after physical stress. Samples 1–5 were measured in experiment 1 (consecutive treatment experiment, measurements at day 1, non-stressed and 2, stressed), samples 6–14 in experiment 2 (parallel treatment experiment). The difference in the CH_4 rate increase between the treatments "non-stressed" and "stressed" was significant ($p = 0.003$ and $p = 0.005$ for Exp. 1 and Exp. 2, respectively).

Sample	CH_4 [ng g^{-1} h^{-1}]			$\Delta^{13}CH_4$ [‰ g^{-1} h^{-1}]		
	non-stressed	stressed	ratio stressed/ non-stressed	non-stressed	stressed	ratio stressed/ non-stressed
1	0.52	1.70	3.3	–	–	
2	0.57	1.87	3.3	–	–	
3	0.43	2.41	5.6	–	–	
4*	0.31	1.21	3.9	0.27	0.39	1.4
5*	0.18	1.67	9.1	0.11	0.34	3.2
6	0.37	–		–	–	
7	0.39	–		–	–	
8	0.14	–		–	–	
9*	0.24	–		0.36	–	
10*	0.06	–		0.43	–	
11*	0.40	–		0.79	–	
12*	–	1.26	5.4	–	0.78	1.5
13*	–	0.98	4.2	–	0.63	1.2
14*	–	2.61	11.2	–	1.07	2.0
Mean ± SD	0.33 ± 0.16	1.71 ± 0.57	5.7 ± 2.9	0.39 ± 0.25	0.64 ± 0.30	1.86 ± 0.81

* Supplemented with ^{13}C-Met.

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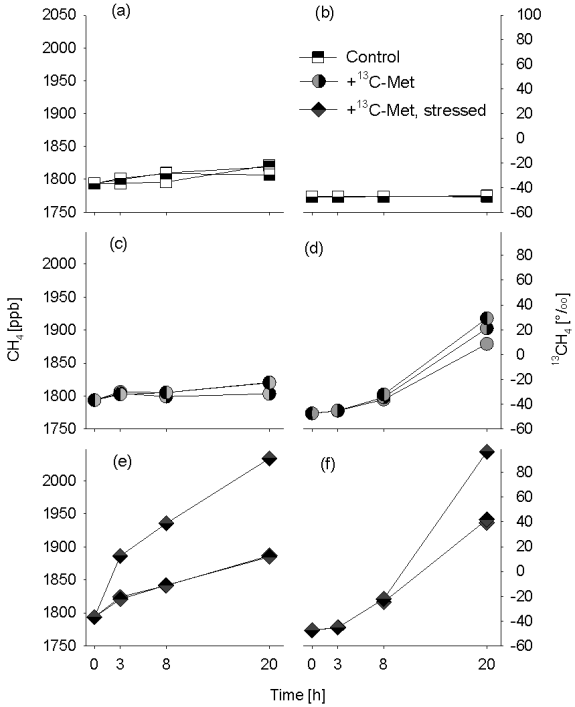

Figure 1. Mixing ratios **(a, c, e)** and $\delta^{13}C$ values **(b, d, f)** of CH_4 produced by *L. angustifolia* (n = 3) in the control flasks **(a, b)** without addition of methionine or physical stress, supplemented with ^{13}C-labelled Met without physical stress **(c, d)**, and supplemented with ^{13}C-labelled Met and the application of physical stress **(e, f)**. Different symbols mark the replicates per treatment. Methane emission rates between the control plants and plants supplemented with $^{13}CH_3$-Met were not different ($p > 0.05$), whereas physical stress induced a significant increase in CH_4 emission rates ($p = 0.005$). Addition of $^{13}CH_3$-Met resulted in a significant increase in the $^{13}CH_4$ signal.

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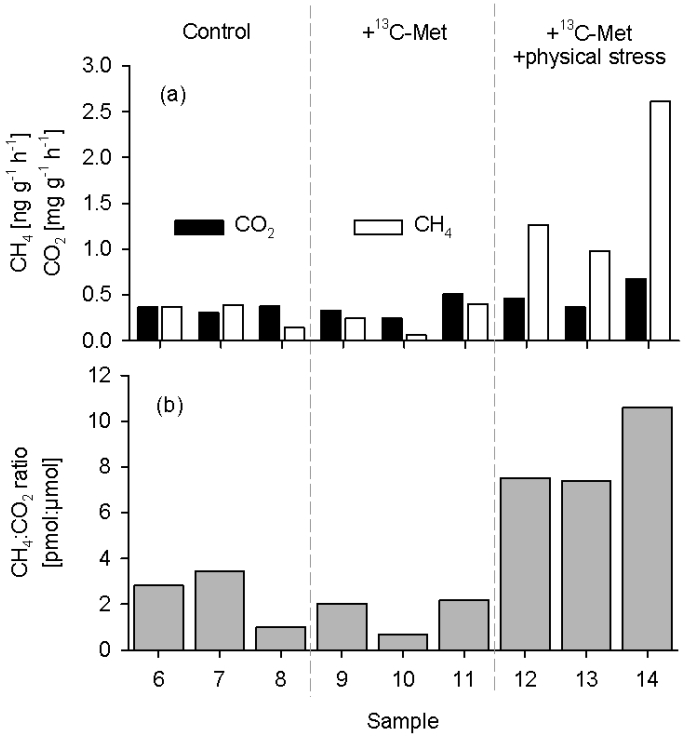

Figure 2. (a) Methane and CO_2 emissions of *L. angustifolia* supplemented with ^{13}C-labelled Met under non-stressed conditions and after application of physical stress, and **(b)** CH_4 to CO_2 emission ratio. Control plants were not supplemented with Met or exposed to physical stress.

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