Methyl Isothiocyanate Concentration, Distribution, and Persistence in Sandy Soil as Influenced by Dazomet Post-application Practices

Estefania G. Polli[1], Travis W. Gannon[1], Ronald R. Rogers[1], Mathieu C. LeCompte[1], Khalied Ahmed[1], and Charles Silcox[2]

Keywords. dazomet, fumigant, methyl isothiocyanate, turfgrass, weed

Abstract. Dazomet is a fumigant commonly used to control soil seedbanks and plant tissues of weed species in highly infested turfgrass areas. This fumigant reacts with water in the soil when in the presence of oxygen and releases methyl isothiocyanate (MITC) gas that kills seeds and plant tissues within the soil. Previous studies have reported varying levels of weed control by dazomet. As MITC is highly water soluble, mobile in soil, and volatile, inconsistencies in dazomet efficacy may be related to post-application practices of tilling, rolling, irrigation, and tarping. Therefore, the objective of this study was to analyze the effect of two practices commonly performed following dazomet application: tarp treatment (tilling, rolling, irrigation, and tarping), and water-seal treatment (post-irrigation at 0, 1, 2, and 3 days after application) on MITC concentration, distribution, and persistence in sandy soil. Field studies were conducted at Sandhills Research Station in Jackson Springs, NC, USA, in 2022 and 2023. MITC concentration and persistence varied between treatments and years. In 2022, MITC concentrations were notably higher in the tarp treatment compared with the water-seal treatment, whereas in 2023, the difference between treatments was less pronounced and more soil depth– and sample timing–dependent. Both treatments presented longer persistence, up to 168 hours after application (HAA), in 2023 compared with 120 HAA in 2022. In addition, MITC was highly concentrated in the top 15 cm of the soil and was detected as deep as 31 cm down from the soil surface in both treatments across both years.

Turfgrass is a major component of landscapes, recreational areas, and urban environments in the United States. The estimated area occupied by turfgrass in the country is 163,812 km^2, which is three times larger than irrigated corn (Milesi et al. 2005). In addition to its aesthetic value, turfgrass areas endow environmental, ecological, economic, and health and well-being benefits for society (Beard and Green 1994; Monteiro 2017; Stier et al. 2013). Weed management is essential to maintain attractive, healthy, and functional turfgrass areas because weeds compete for water, nutrients, and light with turfgrass species, which can reduce its quality (Bingham et al. 2017; Duble 1996). Herbicides are a primary tool for weed management in turfgrass systems (Elmore et al. 2023). Selective herbicides are widely used to control target-specific weed species without harming desired turfgrass species (McElroy and Martins 2013); however, depending on the weed species and extent of the infestation, selective herbicide options are limited and turfgrass renovation becomes necessary to restore the area.

Renovation of turfgrass is one of the most effective methods for eradicating weed species in turfgrass systems (Skorulski 2013). A common parameter used to determine the renovation program is the proportion of desirable turfgrass to weed species in the area. In less infested areas, multiple applications of nonselective post-emergence herbicides are applied to control existing turfgrass and weed species followed by seeding of desired turfgrass cultivar (Park and Landschoot 2003). In heavily infested areas where soil seedbank of weed species is abundant, sod is removed followed by soil sterilization to eliminate soil seedbank and, consequently, minimize contamination of newly established turfgrass (Harper 1994).

Dazomet is the most used soil fumigant in turfgrass systems since the methyl-bromide phaseout in 2005 (California Department of Pesticide Regulation 2021). This pesticide is a granular soil fumigant that controls fungi, bacteria, nematodes, and weed seeds in the soil. When dazomet is incorporated into moist aerated soil, it degrades into several volatile intermediate compounds including MITC gas, which is the primary bioactive compound (Di Primo et al. 2003). Previous studies have reported variable levels of weed control by dazomet. According to Park and Landschoot (2003) and Eitel (1993), dazomet inhibits germination and emergence of multiple weed species, including annual grasses and broadleaf species. Contrarily, Jeffries et al. (2017) and García-Méndez et al. (2008) reported variable grass and broadleaf weed control by this fumigant. This inconsistency in weed control may be related to dazomet environmental fate following its application. Dazomet is highly volatile, water soluble, and soil mobile, which can lead to a multipath simultaneous fate process, such as gases partitioning to soil air, water, and solid phase through diffusion and sorption, degradation, leaching, and atmospheric emission (Ajwa et al. 2010). Adequate concentration, uniform distribution, and sufficient persistence of dazomet in soil are crucial to achieving satisfactory weed control (Ajwa et al. 2010).

Tillage and tarping are practices commonly performed after dazomet application to increase weed control (Jeffries et al. 2017). Tillage provides proper incorporation and distribution of the product in the soil profile, and tarping seals the soil to maintain MITC within the treated area and reduce potential leaching (Ajwa et al. 2010;

Received for publication 12 Aug 2024. Accepted for publication 9 Oct 2024.

Published online 12 Feb 2025.

[1]Department of Crop and Soil Sciences, North Carolina State University, Raleigh, NC 27695, USA

[2]AMVAC Chemical Corporation, Newport Beach, CA 92660, USA

We gratefully acknowledge the financial support of AMVAC Chemical Corporation, and the assistance of Sandhills Research Station staff, and undergraduate assistants, who worked in the Pesticide and Trace Element Fate and Behavior Research Group from 2021 to 2023.

E.G.P., R.R.R., and M.C.L. are Graduate Research Assistants.

T.W.G. is a Professor.

K.A. is a Research Chemist.

C.S. is a Product Development Manager.

E.G.P. is the corresponding author. E-mail: egomier@ncsu.edu

https://doi.org/10.21273/HORTTECH05520-24

Zhang and Wang 2007). However, tillage can be an intensive practice due to the mechanical manipulation of the soil, and tarping is logistically difficult, labor-intensive, and expensive, particularly over large areas. In these cases, irrigation can be a less intensive and expensive alternative to tillage and tarping, as water may function as a seal to minimize MITC atmospheric emissions while proving adequate dazomet incorporation in the treated area by moving it in the soil profile without causing soil disturbance.

Although numerous studies have demonstrated that proper irrigation management following dazomet application can reduce MITC atmospheric emissions (Simpson et al. 2010; Sullivan et al. 2004; Zheng et al. 2006), there is limited information in the literature regarding the influence of practices performed post-dazomet application on MITC concentration, distribution, and persistence in the soil. Therefore, the objective of this study was to analyze the effect of two practices commonly performed following dazomet application: 1) tilling, rolling, irrigating, and tarping, and 2) irrigation at 0, 1, 2, and 3 d after application on MITC concentration, distribution, and persistent following dazomet application in sandy soil under field conditions.

Materials and methods

Experimental site. Field studies were conducted on 20 Jul 2021 and Jun 2022 at Sandhills Research Station in Jackson Springs, NC, USA (35.18°N, 79.68°W) on bare ground consisting of Candor sand (sandy, kaolinitic, thermic Grossarenic Kandiudults; 92%, 4%, and 4% sand, silt, and clay, respectively) with a pH ranging from 5.6 to 5.9 and organic matter content of ≤1.5% (wt/wt) (Fig. 1). Three days before study initiation, the field site was scalped at 1.3 cm cut height and daily irrigated to achieve soil saturation. However, 24 h before initiation, irrigation was ceased to allow the soil to reach field capacity.

Treatment design. Studies were organized as a split-split-plot design of 2 × 11 × 6 in which the whole plot (5.5 m × 10.1 m) was the post-dazomet (Basamid® G, AMVAC Chemical Corporation, Newport Beach, CA, USA) application practice (tarp treatment and water-seal treatment), sub-plot (1.0 m × 5.5 m) the sample timing (2, 9, 16, 24, 36, 48, 72, 120, 168, and 240 HAA), and sub-sub-plot (0.9 m × 1.0 m) the sampling depth (0 to 4 cm, 4 to 8 cm, 8 to 11 cm, 11 to 15 cm, 16 to 23 cm, and 24 to 30 cm), in two experimental runs containing three replications each.

Fig. 1. Experimental site at the Sandhills Research Station in Jackson Springs, NC, USA.

Treatment and application information. Two post-dazomet application practices were tested in this study. For both practices, dazomet application was performed on bare ground using a drop spreader (Model SSD 10006152; The Andersons, Maumee, OH, USA) calibrated to deliver 472 kg·ha^{-1} a.i., which corresponds to the maximum label rate for greens and tees when using mechanical incorporation. For practice (1), subsequently to dazomet application, plots were tilled to 10-cm depth using a tractor-mounted rotary tiller, then rolled using a custom-built roller, and irrigated with 15 mm of water to activate dazomet. Following irrigation, plots were tarped using clear 6-mm-thick plastic sheets and then sealed by covering the perimeter with nontreated soil. After the minimum required time of 5 d (120 h) after application, as specified by the label, the tarps were removed (AMVAC 2014). Although the label recommends tarping the soil and then watering with a drip irrigation system, the absence of such a system at the experimental site required the use of sprinkler irrigation before tarping. For practice (2), subsequently to dazomet application, plots received 15 mm of water to activate dazomet and seal the soil surface. In addition, plots were irrigated at 13 mm, 6 mm, and 3 mm at 1, 2, and 3 d after treatment, respectively. The amount of irrigation decreased over time to avoid runoff of dazomet between plots and off-site. It is important to note that the maximum labeled rate for practice (2), which uses water incorporation instead of mechanical incorporation as in Practice (1), is 294 kg·ha^{-1} a.i. However, for comparison purposes, 472 kg·ha^{-1} a.i. was used for both practices, which is 60% higher than the label rate for water incorporation. Practices (1) and (2) are referred to as tarp and water-seal treatments, respectively, for the remainder of this article. Weather conditions during the study were continuously monitored and recorded using a weather station from the North Carolina Agricultural Research Service (Table 1).

Sample collection. Soil air samples were collected using an AMS 12 GVP soil gas probe (AMS™, American Falls, ID, USA). A three-way lure lock stop valve was used to connect a 30-mL syringe and a piece of 10 inches of plastic tubing in which a metal tip was inserted to connect the soil gas probe after its insertion into the soil. A two-way lure lock stop valve was fitted to the tip of a 60-mL syringe and connected to the third port of the three-way lure lock stop valve (Fig. 2). For tarp treatment, the tarp was cut with a utility knife, and the soil gas probe was inserted into the soil. Once the soil gas probe reached the desired depth, its internal rod was removed, and the metal tip connected to the sampling apparatus was fastened to its upper part. To clean the void volume of the soil air probe and plastic tubing before soil gas collection, 30 mL of air was removed using the 30-mL syringe. In sequence, the three-way valve was closed to allow air to be pulled via the 60-mL syringe while preventing air movement to or from the 30-mL

Table 1. Weather and soil parameters throughout duration of studies at Sandhills Research Station in Jackson Springs, NC, USA.[i]

Sample timing (HAA)[ii]	Air temp	Air RH[ii]	Soil temp[iii]	Rainfall[iv]
	°C	%	°C	mm
		2022		
2	23	51	28	0
9	24	67	29	15
16	25	79	30	0
24	26	64	30	0
36	23	53	29	0
48	23	72	28	0
72	24	85	28	0
120	29	71	30	0
168	29	70	31	10
240	26	73	30	0
Average	25	69	29	25[iv]
		2023		
2	19	91	21	0
9	20	81	21	15
16	21	79	22	0
24	22	75	23	0
36	24	61	24	0
48	18	80	23	0
72	19	77	23	0
120	22	70	23	0
168	20	63	23	0
240	20	46	23	0
Average	20	72	23	15[iv]

[i] Experiments were conducted from 6 Jun 2022 to 16 Jun 2022, and from 30 May 2023 to 9 Jun 2023.
[ii] Abbreviations: HAA (hours after application), RH (relative humidity).
[iii] Temperature collected at depth of 25 cm from soil surface.
[iv] Cumulative rainfall throughout the study duration in 2022 and 2023.

syringe. The two-way valve connected to the 60-mL syringe was then opened and 60 mL of air was pulled from the soil. Immediately on sample collection, the two-way valve connected to the 60-mL syringe was closed to prevent gas escape and the syringe was carefully removed from the sampling apparatus. A 23G needle was attached to the 60-mL syringe and then inserted into a headspace vial containing 1 mL of ethyl acetate GC grade where the soil air was slowly deposited. Vials were stored on ice in a cooler and transported to the laboratory where MITC residue analysis was performed.

Fig. 2. Soil gas collection using an AMS 12 GVP soil gas probe (AMS™, American Falls, ID, USA) in the tarped treatment.

Sample analytical procedure. MITC concentrations were determined using an Agilent 7890/7010 triple-quadruple mass spectrometry system coupled with headspace gas chromatography (GC-MS/MS). Each sample was prepared in 20-mL headspace vials (Fisher Scientific Optima), containing 1 mL of ethyl acetate per vial. To minimize volatile losses, the magnetic screw vial caps (CTC Analytics) were equipped with a polytetrafluoroethylene lining. Over a 10-min duration, the samples were heated to 60 °C under constant agitation (500 rpm) with a shaking cycle of 5 s followed by a 2-s rest in a specialized headspace autosampler (CTC Analytics CombiPal). Subsequently, a 300-µL headspace aliquot was precisely injected into the GC-MS (Agilent 7890 GC, Agilent 7010 MS). To prevent any MITC recondensation in the syringe, the autosampler syringe was maintained at 65 °C. The GC (gas chromatography) inlet was set at 200 °C with a 1:5 split ratio. The separation of compounds was achieved using a DB 624 Ultra Inert column (20 m × 0.18 mm × 1.00 µm, JandW), using helium as the carrier gas with a flow rate of 0.7 $mL \cdot min^{-1}$. The GC oven program commenced at 35 °C, held for 0.75 min, and was then ramped up to 240 °C at a rate of 15 $°C \cdot min^{-1}$. The transfer line was maintained at 250 °C. The ion source of the GC-MS operated in positive chemical ionization mode to detect MITC, using methane as the reagent gas (1 $mL \cdot min^{-1}$). The source temperature was set at 300 °C, and the ionization energy was maintained at 150 eV. Helium quench gas (2.25 $mL \cdot min^{-1}$) and nitrogen collision gas (1.5 $mL \cdot min^{-1}$) were used in the collision cell. Selected-ion monitoring was used to quantify MITC using the most prevalent ion ($m/z = 74$). Compound identity was verified by the response ratio between the quantitation ion and the qualifier ion ($m/z = 73$). An internal standard, eluting at 4.64 min with $m/z = 75$, present in the ethyl acetate used for calibration and site samples, was used to correct response variability. For calibration standards, 1 mL of ethyl acetate was added to sealed headspace vials, along with a known quantity of MITC (Aldrich 97%), achieving targeted MITC masses per vial (0.1, 0.3, 1, 3, 10, 30, 100, 300 µg MITC per vial for calibration samples, and 5 µg MITC per vial for quality control samples). Calibration standards were prepared using an MITC stock solution (100 $\mu g \cdot \mu L^{-1}$ in ethyl acetate), stored at −20 °C. These standards were prepared on the same day as the sampling to ensure consistent volatile loss conditions. Both calibration standards and samples were analyzed within 5 d of preparation or collection, with typical hold times ranging from 1 to 2 d. A quadratic regression equation was employed to describe the results obtained for calibration standards, demonstrating a high coefficient of determination (R^2 > 0.95). The recovery for calibration and quality control samples was found to be 100% and 105%, respectively. For site samples, a 60-mL volume of gas was extracted from the soil gas phase and slowly bubbled through the ethyl acetate in the vial at a controlled rate of 0.5 $mL·s^{-1}$ to capture the MITC from the entire 60-mL volume. The recovery of this sampling method was verified using a known concentration of 94 µg of MITC in a 60-mL gas sample, yielding a recovery rate of 108%.

Statistical analysis. MITC concentration data were subjected to analysis of variance in SAS software (Cary, NC, USA) version 9.4 using PROC GLIMMIX and treatment means were computed using Tukey's honestly significant difference test at α = 0.05. Square root transformation was performed to normalize data. Experimental run and whole-plot, subplot, and sub-sub-plot treatments were considered fixed effects, while replication was considered a random effect.

Results

Experimental runs were significantly different at α = 0.05. Thus, means were presented separately for each experimental run or year (2022, 2023). Furthermore, for both years, the two-way interactions between post-dazomet application practice, sample timing, and soil depth were significant at α = 0.05.

Post-dazomet application practice and sample timing. In 2022, the concentration of MITC was 3.6 times higher in the tarp treatment than in the water-seal treatment from 2 to 120 HAA, whereas no differences were observed between the two treatments at the latest sample timings, 168 and 240 HAA (Table 2). Conversely, in 2023, the MITC concentrations were higher in the water-seal treatment at 2, 9, 16, and 168 HAA compared with the tarp treatment, while at 36, 48, and 120 HAA, MITC concentrations were higher in the tarp treatment compared with the water-seal treatment, similar to 2022. In addition, no differences were observed between treatments at 24, 72, and 240 HAA. The peak MITC concentration occurred at 36 HAA in the tarp treatment for both years. However, in the water-seal treatment, the peak occurred at 36 HAA in 2022 but shifted to 9 HAA in 2023. Furthermore, immediately after the 120 HAA sample collection, the tarp was removed from the tarp treatment, resulting in a 24% and 21% decrease in MITC concentration in 2022 and 2023, respectively, compared with the previous sample collection (data not shown). In terms of persistence, MITC was detected up to 120 HAA in the tarp treatment and 72 HAA in the water-seal treatment in 2022, whereas in 2023, it was detected up to 168 HAA in both treatments.

Table 2. Effect of the interaction between post-dazomet application practice and sample timing averaged over soil depth on methyl isothiocyanate (MITC) concentration in the soil air.[i,ii,iii]

	2022		2023	
Hours after treatment	Tarp[iv]	Water-seal[v]	Tarp[iv]	Water-seal[v]
	ng·mL^{-1}			
2	22.3 A c	9.6 B c	0.0 B d	4.0 A e
9	121.7 A b	30.3 B b	78.0 B b	139.5 A a
16	145.8 A b	21.9 B c	40.8 B c	58.3 A bc
24	145.2 A b	23.3 B c	45.2 A c	48.6 A c
36	249.9 A a	101.8 B a	91.7 A a	72.8 B b
48	172.3 A b	84.1 B a	36.8 A c	20.7 B d
72	128.3 A b	12.0 B d	50.7 A bc	37.3 A c
120	29.8 A c	0.0 B e	48.4 A bc	30.2 B cd
168	0.0 A d	0.0 A e	2.9 B d	11.8 A e
240	0.0 A d	0.0 A e	0.0 A d	2.4 A e
Sum	1015.3	282.9	394.5	425.6

[i] Data from experimental runs 1 and 2 conducted in 2022 and 2023, respectively, at Sandhills Research Station in Jackson Springs, NC, USA.
[ii] Dazomet was applied at 472 kg·ha^{-1} a.i.
[iii] Means followed by the same letter in the column do not differ using Tukey's test at α = 0.05. Uppercase letters represent the mean comparison of the main effect of dazomet post-application practice within rows and lowercase letters the main effect of sample timing within columns.
[iv] Dazomet application was followed by tillage, rolling, irrigation (15 mm), and tarping. Tarp was removed following sample collection at 120 h.
[v] Irrigation of 13 mm, 6 mm, and 3 mm at 1, 2, and 3 d after application in addition to 15 mm irrigated subsequently to application.

Post-dazomet application practice and soil depth. MITC concentrations were consistently higher across all depths in the tarp treatment than in the water-seal treatment in 2022 (Table 3). However, in the following year, MITC concentrations varied between treatments across different soil depths. Specifically, MITC concentrations were higher in the tarp treatment compared with the water-seal treatment for two soil depth ranges (0.0 to 4.0 cm and 8.1 to 12.0 cm), but lower for one depth range (23.1 to 30.0 cm). Moreover, concentrations were similar between the two treatments at the other soil depth ranges. In the tarp treatment, MITC was primarily concentrated in the top 15 cm of the soil column in 2022, accounting for 80% of the total concentration. This distribution contrasted with the top 8 cm in 2023, which accounted for 52.4% of the total concentration. Similarly, for the water-seal treatment, the highest MITC concentrations were detected in the top 12 cm of the soil column in 2022, accounting for 76% of the total concentration. Nonetheless, in 2023, the distribution shifted, with the highest concentration restricted to the soil depth of 4.1 to 8.0 cm, which accounted for 28% of the total concentration. Overall, across both years and methods, 80% to 89% of MITC was detected in the top 15 cm of soil.

Timing and soil depth. The distribution of MITC across soil depths varied from 2 to 120 HAA in 2022 (Table 4). At 2 and 120 HAA, MITC was highly concentrated from 0 to 23 cm soil depth. In 2023, MITC concentration decreased in shallower depths while increasing in deeper depths as time progressed. For example, MITC was detected from 0 to 31 cm at 120 HAA, whereas it was only detected from 23.1 to 31 cm at 240 HAA. Furthermore, in 2022, the peak of MITC concentration consistently occurred from 36 to 48 HAA across all soil depths. Nonetheless, in 2023, MITC concentration peak highly varied depending on the depth range. Peaks were observed between 9 and 36 HAA from

Table 3. Effect of the interaction between post-dazomet application practice and soil depth averaged over sample timing on methyl isothiocyanate (MITC) concentration in the soil air.[i,ii,iii]

Soil depth (cm)	2022		2023	
	Tarp[iv]	Water-seal[v]	Tarp[iv]	Water-seal[v]
	ng·mL^{-1}			
0.0–4.0	104.5 A ab	52.1 B ab	56.9 A ab	48.4 B b
4.1–8.0	128.6 A a	32.1 A a	67.2 A a	70.7 A a
8.1–12.0	143.6 A ab	44.8 B ab	49.1 A b	37.0 B b
12.1–15.0	112.0 B b	21.8 A ab	29.7 B c	47.7 B b
15.1–23.0	70.5 A bc	13.5 A b	19.3 B d	32.8 B b
23.1–31.0	50.0 B c	5.4 A b	14.5 B e	18.8 A c
Sum	609.2	169.7	236.7	255.4

[i] Data from experimental runs 1 and 2 conducted in 2022 and 2023, respectively, at Sandhills Research Station in Jackson Springs, NC, USA.
[ii] Dazomet was applied at 472 kg·ha^{-1} a.i.
[iii] Means followed by the same letter in the column do not differ using Tukey's test at $\alpha = 0.05$. Uppercase letters represent mean comparison of the main effect of dazomet post-application practice within rows and lowercase letters the main effect of soil depth within columns.
[iv] Dazomet application was followed by tillage, rolling, irrigation (15 mm), and tarping. Tarp was removed following sample collection at 120 h.
[v] Irrigation of 13 mm, 6 mm, and 3 mm at 1, 2, and 3 d after application in addition to 15 mm irrigated subsequently to application.

0 to 15 cm, while at depths of 15.1 to 31 cm, the peak occurred at 120 HAA.

Discussion

The concentration of MITC was higher in the tarp treatment compared with the water-seal treatment for most sample timings in 2022, consistent with previous studies (Wang et al. 2006; Zhang and Wang 2007). However, in 2023, higher MITC concentrations were observed at earlier sample timings in the water-seal treatment and at later sample timings in the tarp treatment. Furthermore, MITC persistence in the soil column was shorter in 2022 compared with 2023 for both treatments. This reversal of MITC concentration and persistence between years may be attributed to differences in the soil temperature. In 2022, the average soil temperature throughout the study was higher than in 2023, potentially accelerating the conversion rate from dazomet to MITC and MITC loss from the soil into the atmosphere through degradation and volatilization (Dungan et al. 2003; Ren et al. 2022). Nonetheless, the presence of the tarp created a physical barrier that effectively retained MITC within the soil column and maintained its peak timing consistently at 36 HAA across both years, despite variations in soil temperature. Contrary to findings of this study, Wang et al. (2006) observed a peak in MITC concentration in the tarp treatment as early as 7 HAA. Previous studies have reported the effectiveness of water-seal in reducing MITC volatilization (Gao et al. 2008; Nelson et al. 2012; Simpson et al. 2010; Sullivan et al. 2004). However, higher water evaporation rates in 2022, driven by elevated air temperatures, potentially reduced water availability for effectively sealing MITC in the soil. Consequently, this resulted in lower MITC concentrations and persistence, as well as varying peak timing, compared with 2023 in water-seal treatment.

Soil temperature may also have influenced variations of MITC concentration and distribution in the soil column between treatments across years. Although MITC concentrations were consistently higher across all soil depths in the tarp treatment compared with the water-seal treatment in 2022, differences between treatments were less pronounced in 2023. As discussed previously, elevated temperatures likely accelerated the conversion of dazomet into MITC in the soil, accentuating differences between years. Moreover, in 2022, the highest MITC concentrations were observed at deeper soil depths compared with 2023, which aligns with the finding of Nelson et al. (2012), who observed a high concentration of MITC in the top 12 cm of the soil column. The higher cumulative rainfall in 2022, compared with 2023, possibly facilitated MITC movement to deeper depths in the soil column. As described in the methodology, dazomet was incorporated at 10-cm soil depth, while no incorporation was performed in water-seal treatment. Results revealed the presence of MITC as deep as 31 cm from the soil surface, suggesting that dazomet migrated 21 cm and 31 cm from the application zone in the tarp and water-seal treatments, respectively. Similarly, in a study conducted by Zhang and Wang (2007), MITC was detected at soil depths as deep as 20 and 40 cm down from the application zone in the water-seal and tarp treatments, respectively. Thus, findings of this present study and those of Zhang and Wang (2007) suggest that the downward movement of MITC in the soil column from the application zone possibly occurred as a result of water infiltration from both irrigation and rainfall since MITC has high solubility in water and weak soil adsorption (Dungan et al. 2003; Frick 1996).

In terms of MITC distribution in the soil column, MITC concentrations in 2022 decreased with depth. However, in 2023, concentrations increased over time at deeper depths while declining at shallower depths. The lower temperatures and cumulative rainfall in 2023 compared with the previous year may have slowed down dazomet conversion into MITC and movement down the soil column, respectively, contributing to the differences in MITC distribution between the 2 years.

Conclusion

The findings of this study illustrate the complex dynamics of MITC behavior and fate in the soil. Notably, soil temperature influenced the variations in concentration, persistence, and distribution of MITC between tarp and water-seal treatments across study years. This influence is attributed to the direct impact of soil temperature on critical processes, including the conversion rate of dazomet into MITC, soil water evaporation, and degradation and volatilization of MITC into the atmosphere. Given the limited literature on this subject, this study serves as a foundation for advancing the comprehension of MITC dynamics in the environment. Its implications extend beyond weed control, encompassing the management of fungi, bacteria, and nematodes, as dazomet is recommended for use against a broader range of pests.

Table 4. Effect of the interaction between soil depth and sample timing averaged over post-dazomet application practice on methyl isothiocyanate (MITC) concentration in the soil air.[i,ii,iii]

	Soil depth (cm)						
Hours after treatment	0.0–4.0	4.1–8.0	8.1–12.0	12.1–15.0	15.1–23.0	23.1–31.0	Sum
	ng·mL^{-1}						
2022							
2	27.8 A e	11.5 AB d	18.1 A e	17.3 A d	14.3 AB bc	6.5 B d	95.6
9	117.2 A c	134.3 A b	87.2 AB d	72.3 B c	35.7 B b	9.3 C cd	455.9
16	110.6 A cd	141.5 A b	141.1 A c	46.7 BC d	47.3 B b	15.9 C cd	503.2
24	103.7 A d	85.9 A c	132.7 A cd	120.0 A b	40.1 B c	23.1 B cd	505.4
36	159.2 B d	198.8 B a	255.4 A a	185.7 BC a	124.8 C a	131.2 C a	1055.1
48	171.5 A a	141.2 B b	162.6 AB b	120.8 BC b	99.6 C a	73.7 C b	769.3
72	84.1 AB d	75.9 B c	118.2 A d	82.8 B c	42.1 C c	17.6 C cd	420.6
120	8.7 AB f	14.6 AB e	26.9 A e	23.2 A d	16.1 AB d	0.0 B e	89.4
168	0.0 A f	0.0 A f	0.0 A f	0.0 A e	0.0 A e	0.0 A e	0.0
240	0.0 A f	0.0 A f	0.0 A f	0.0 A e	0.0 A e	0.0 A e	0.0
Sum	782.8	803.6	942.1	668.8	420.0	277.2	
2023							
2	0.0 B e	8.2 A e	0.0 B d	0.0 B d	3.8 B e	0.0 B d	12.0
9	174.5 A a	179.5 A a	69.4 D bc	115.0 B a	74.1 C a	40.0 E b	652.4
16	82.6 A b	93.8 A b	69.7 B ab	26.4 C c	11.8 D de	13.0 D bc	297.3
24	69.0 B b	105.2 A b	61.6 B b	25.0 C c	14.2 D d	6.5 E	281.4
36	92.8 B b	150.6 A a	91.8 B a	94.8 B a	31.8 C Bc	32.0 C a	493.7
48	30.5 B cd	44.3 AB d	43.1 A c	30.3 B c	21.2 C c	3.2 D cd	172.5
72	45.0 B c	59.6 A c	53.1 A bc	50.7 A b	39.7 B b	15.9 C bc	263.8
120	32.0 B d	48.0 A cd	33.9 B c	44.8 A bc	46.8 A ab	30.4 B a	235.9
168	0.0 C e	0.0 C f	8.2 B d	0.0 C d	17.6 A d	18.5 A bc	44.3
240	0.0 B e	0.0 B f	0.0 B d	0.0 B d	0.0 B e	7.1 A c	7.1
Sum	526.3	689.2	430.7	386.9	260.9	166.3	

[i] Data from experimental runs 1 and 2 conducted in 2022 and 2023, respectively, at Sandhills Research Station in Jackson Springs, NC, USA.

[ii] Dazomet was applied at 472 kg·ha^{-1} a.i.

[iii] Means followed by the same letter in the column do not differ using Tukey's test at $\alpha = 0.05$. Uppercase letters represent mean comparison of the main effect of soil depth within rows and lowercase letters the main effect of sample timing within columns.

References cited

Ajwa H, Ntow WJ, Qin R, Gao S. 2010. Properties of soil fumigants and their fate in the environment, p 315–330. In: Krieger R (ed). Hayes' handbook of pesticide toxicology. Academic Press, Amsterdam, The Netherlands. https://doi.org/10.1016/B978-0-12-374367-1.00009-4.

AMVAC. 2014. Basamid® G herbicide product label. EPA Reg. No.5481-9027. AMVAC Chemical Corporation, Los Angeles, CA, USA.

Beard JB, Green RL. 1994. The role of turfgrasses in environmental protection and their benefits to humans. J Environ Qual. 23(3):452–460. https://doi.org/10.2134/jeq1994.00472425002300030007x.

Bingham SW, Chism WJ, Bhowmik PC. 2017. Weed management systems for turfgrass, p 603–665. In: Smith AE (ed). Handbook of weed management systems. Routledge, Oxfordshire, England, UK. https://doi.org/10.1201/9780203752470.

California Department of Pesticide Regulation. 2021. Annual statewide pesticide use report indexed by commodity. https://www.cdpr.ca.gov/docs/pur/pur21rep/pur_data/pur2021_indexed_by_chemical.pdf. [accessed 23 Jan 2024].

Di Primo P, Gamliel A, Austerweil M, Steiner B, Beniches M, Peretz-Alon I, Katan J. 2003. Accelerated degradation of metam-sodium and dazomet in soil: Characterization and consequences for pathogen control. Crop Prot. 22(4):635–646. https://doi.org/10.1016/S0261-2194(03)00004-8.

Duble RL. 1996. Turfgrasses: Their management and use in the southern zone. Texas A&M University Press, College Station, TX, USA.

Dungan RS, Gan J, Yates SR. 2003. Accelerated degradation of methyl isothiocyanate in soil. Water, Air, and Soil Pollution. 142(1/4):299–310. https://doi.org/10.1023/A:1022092907878.

Eitel J. 1993. The effectiveness of dazomet* as influenced by the use of plastic sheeting. Acta Hortic. 382:104–109. https://doi.org/10.17660/ActaHortic.1995.382.10.

Elmore MT, Patton AJ, Gannon TW, Brosnan JT. 2023. Advances in turfgrass weed management. Burleigh Dodds Science Publishing Limited, Cambridge, England, UK.

Frick AV. 1996. Behavior of methylisothiocyanate under varying soil water regime and soil properties (PhD Diss). University of British Columbia, Vancouver, BC, Canada.

Gao S, Trout TJ, Schneider S. 2008. Evaluation of fumigation and surface seal methods on fumigant emissions in an orchard replant field. J Environ Qual. 37(2):369–377. https://doi.org/10.2134/jeq2007.0088.

García-Méndez E, García-Sinovas D, Becerril M, De Cal A, Melgarejo P, Martínez-Treceño A, Fennimore SA, Soria C, Medina JJ, López-Aranda JM. 2008. Chemical alternatives to methyl bromide for weed control and runner plant production in strawberry nurseries. HortScience. 43(1):177–182. https://doi.org/10.21273/HORTSCI.43.1.177.

Harper JC II. 1994. Renovation of lawns. Penn State Extension. https://extension.psu.edu/renovation-of-lawns. [accessed 14 Apr 2024].

Jeffries MD, Gannon TW, Reynolds WC, Yelverton FH, Silcox CA. 2017. Herbicide applications and incorporation methods affect dazomet efficacy on bermudagrass. HortTechnology. 27(1):24–29. https://doi.org/10.21273/HORTTECH03564-16.

McElroy JS, Martins D. 2013. Use of herbicides on turfgrass. Planta daninha. 31(2): 455–467. https://doi.org/10.1590/S0100-83582013000200024.

Milesi C, Running SW, Elvidge CD, Dietz JB, Tuttle BT, Nemani RR. 2005. Mapping and modeling the biogeochemical cycling of turf grasses in the United States. Environ Manage. 36(3):426–438. https://doi.org/10.1007/s00267-004-0316-2.

Monteiro JA. 2017. Ecosystem services from turfgrass landscapes. Urban Forestry and Urban Greening. 26:151–157. https://doi.org/10.1016/j.ufug.2017.04.001.

Nelson SD, Simpson CR, Ajwa HA, Williams CF. 2012. Evaluating surface seals in soil columns to mitigate methyl isothiocyanate volatilization, p 567–580. In: Larramendy ML, Solonesk S (eds). Integrated pest management and pest control–Current and future tactics. InTech, Rijeka, Croatia.

Park BS, Landschoot PJ. 2003. Effect of dazomet on annual bluegrass emergence and creeping bentgrass establishment in turf maintained as a golf course fairway. J Crop Sci. 43(4):1387–1394. https://doi.org/10.2135/cropsci2003.1387.

Ren L, Li W, Li Q, Zhang D, Fang W, Li Y, Wang Q, Jin X, Yan D, Cao A. 2022. Effects of granule size ranges on dazomet degradation and its persistence with different environmental factors. Agriculture. 12(5):674. https://doi.org/10.3390/agriculture12050674.

Simpson CR, Nelson SD, Stratmann JE, Ajwa HA. 2010. Surface water seal application to minimize volatilization loss of methyl isothiocyanate from soil columns. Pest Manage Sci. 66(6):686–692. https://doi.org/10.1002/ps.1930.

Skorulski J. 2013. Better grasses make for better fairways. USGA Green Section Record. 51:1–3.

Stier JC, Steinke K, Ervin EH, Higginson FR, McMaugh PE. 2013. Turfgrass benefits and issues. Turfgrass: Biol, Use, and Manage. 56:105–145. https://doi.org/10.2134/agronmonogr56.c3.

Sullivan DA, Holdsworth MT, Hlinka DJ. 2004. Control of off-gassing rates of methyl isothiocyanate from the application of metam-sodium by chemigation and Shank injection. Atmos Environ. 38(16):2457–2470. https://doi.org/10.1016/j.atmosenv.2004.02.002.

Wang D, Fraedrich SW, Juzwik J, Spokas K, Zhang Y, Koskinen WC. 2006. Fumigant distribution in forest nursery soils under water seal and plastic film after application of Dazomet, metam-sodium and chloropicrin. Pest Manag Sci. 62(3): 263–273. https://doi.org/10.1002/ps.1164.

Zhang Y, Wang D. 2007. Emission, distribution and leaching of methyl isothiocyanate and chloropicrin under different surface containments. Chemosphere. 68(3): 445–454. https://doi.org/10.1016/j.chemosphere.2006.12.083.

Zheng W, Yates SR, Papiernik SK, Nunez J. 2006. Conversion of metam-sodium and emission of fumigant from soil columns. Atmos Environ. 40(36):7046–7056. https://doi.org/10.1016/j.atmosenv.2006.06.009.