Introduction

Nitrogen fertilization is one of the main sources of anthropogenic N_2O emission to the atmosphere (Cole et al., 1997). As the main grain crop in eastern Canada, corn requires larger amounts of N than other cereals (Ma et al., 1999, 2003). Robertson et al. (2000) suggest that soil mineral N availability, rather than N fertilization *per se*, regulates the N_2O flux from agricultural soils. Therefore, mineralization, fertilization, and crop uptake of N collectively determine the overall N_2O emission. The timing of soil mineral N released from organic mineralization coincides roughly with the pattern of crop uptake (Ma et al., 1999, 2003; Wu et al., 2008). However, the high N demand by the crop and the practice by farmers of applying more N than the crop requires often result in relatively high mineral N concentrations and thus, relatively large emission of N_2O can occur in corn production systems (Chantigny et al., 1998; Gregorich et al., 2005; Mackenzie et al., 1998; Wagner-Riddle et al., 1997). Zebarth et al. (2008) reported that while delay of fertilizer application to sidedressing with an associated reduction in N fertilizer application reduced soil N levels, there was no effect of these practices on N_2O emission from soil. It is clear that various fertilization regimes exert different influences on the nutrient concentrations at various stages of crop growth, which therefore cause different amounts of N_2O to be produced and released from soil. Achieving a better understanding of emission patterns as affected by fertilizer management is a prerequisite to designing fertilization strategies that optimize yield while minimizing N_2O emissions.

The objectives of this multi-site-yr study were to (1) determine the flux and the total N_2O emission as affected by preplant urea and sidedress liquid urea-ammonium nitrate (UAN) applied at different rates to corn; (2) assess the effect of soil temperature, water content, and NH_4^+- and NO_3^--N concentrations on N_2O emission; and (3) devise a fertilization strategy with reasonable grain yield response and relatively low N_2O emission.

Materials and Methods

In Canada, on-farm experiments on the amount and timing of N fertilizer application to corn were done at Ottawa (45° 18′ N, 75° 43′ W), ON from 2005 to 2007, Guelph (43°34′ N, 80°25′ W), ON and Saint-Valentin (45º05′ N, 73º21′ W), QC in 2006 and 2007. The experiment consisted of a set of treatments comparing preplant and sidedress N application methods: (1) N0, a check with no fertilizer applied, and (2) N30, (3) N90, and (4) N150, where urea was broadcast at 30, 90 and 150 kg N ha^{-1}, respectively, prior to planting. The two sidedress treatments were (5) N30+N60 and (6) N30+N120, in which 30 kg N ha^{-1} was preplant and an additional 60 or 120 kg N ha^{-1}, respectively, of UAN (urea ammonium nitrate) was applied as a single band furrow between adjacent corn rows, at the V6 to V8 growth stage.

The static chamber method was used to monitor the N_2O emission (Rochette and Bertrand, 2008). Gas samples were collected between 10:00 and 12:00 (Eastern Standard Time) on 0, 1, 3, 7, 14, 21, and 28 d after preplant fertilization or sidedress application at the V6-V8 growth stage, and analyzed for N_2O concentration using a gas chromatograph with electron capture detector. The average N_2O flux for each treatment presented in the figures was the arithmetic means of four replications of each treatment. Total cumulative N_2O emission for each treatment was estimated by linear integratation of the area under the N_2O flux curve during the 28-d monitoring period, using the Grapher 5.0 software (Golden Software Inc., Golden, CO, USA).

Data from each site-yr were subjected to analyses of variances according to the Mixed Procedures in SAS using the default restricted maximum likelihood estimation method. Treatment means were separated based on the F-protected $LSD_{0.05}$ test.

Results and Discussion

Fluctuations in rainfall amount and its temporal distribution, soil temperatures and moisture content across the seven site-yrs contributed to the difference in the timing of peaks, peak height ,and the cumulative N_2O emission (Ma et al. 2009).

We observed that without N application, rate of N_2O emission was very low, with an average of 77 μg N m^{-2} h^{-1} and maximum of 360 μg N m^{-2} h^{-1} (Figs. 1, 2 and 3); the small peaks of N_2O flux were most likely caused by soil disturbance due to field operations and rain storms.

Fertilizer effects on N_2O emission varied across the seven site-yrs, but fertilizer treatments resulted in temporally distinct emission peaks, peak height, and the total cumulative N_2O emission (Figs. 1, 2 and 3). In 13 out of the 14 monitoring periods, the influence of fertilizer treatments on N_2O emission peaks were clearly separated. Peak emission rates ranged from about 120 to 800 μg N m^{-2} h^{-1} for preplant N or 30 to 900 μg N m^{-2} h^{-1} for sidedress application, with highest emissions occurring in the highest N treatments.

The cumulative N_2O emission and the calculated FIE (defined as the difference between the cumulative emission from a fertilized treatment and the unfertilized control treatment divided by the amount of N fertilizer applied), based on the 28-d monitoring period after preplant application were affected primarily by the amount of N fertilizer, with treatment N150 having the highest emission. On average, the cumulative N_2O emission during the 28-d period was 0.13 kg N ha^{-1} for N0, but increased rapidly to 1.04 kg N ha^{-1} when fertilizer was at 150 kg N ha^{-1} (Fig. 4a). Accordingly, the calculated FIE values ranged from 0.03% to 1.24%. The mean FIE across all sites was 0.30 and 0.36% for N30 and N90, respectively, and doubled to 0.61% for N150.

The cumulative N_2O emission during the 28-d monitoring period after sidedress application corresponded to the rates of N fertilizer applied across all site-yrs, and averaged 0.34 (ranged 0.08 to 2.22) kg N ha^{-1}. For N30+N60 the mean emission across all site-yrs was 0.56 kg N ha^{-1} and for N30+N120 it was double that amount (1.17 kg N ha^{-1}). Including the initial 28-d period of emission after preplant base application of 30 kg N ha^{-1} and the 28-d period after sidedress application, the cumulative N_2O emission ranged from 0.33 to 2.42 kg N ha^{-1}. The cumulative mean N_2O emission averaged 0.26 kg N ha^{-1} for the N0 control treatment and, with an additional 60 kg N ha^{-1} applied, the cumulative N_2O emission increased > two fold to 0.78 kg N ha^{-1}. By increasing the sidedress N to 120 kg N ha^{-1} the cumulative N_2O emission increased by twofold again to 1.30 kg N ha^{-1}. Accordingly, the calculated FIEs based on the two 28-d monitoring periods averaged 0.54%, with ranges of 0.05 to 1.45%.

It appears that cumulative N_2O emissions averaged across all site-yrs (for 98 sampling dates – 7 site-yr x 7 sampling dates x 2 monitoring periods) for soils receiving sidedress N at the V6-V8 stage were higher ($P=0.07$) than the corresponding N treatments at preplant (Fig. 4a). Caution should be taken when comparing the preplant against sidedress N fertilizer application strategies as the increase of soil moisture and rainfall events after the 28-d monitoring period could have continuously stimulated preplant fertilizer-induced N_2O emissions (which was not measured in this study), resulting in no differences between the two application methods and/or event reverse situations could occur. However, fertilizer-induced N_2O emissions are often short-lived (MacKenzie *et al.* 1998; Bergstrom *et al.* 2001), and proper management practices would substantially reduce N_2O emissions (Adviento-Borbe *et al*. 2007). In this study, preplant N fertilizer was immediately incorporated into the deep soil after application (same day), which may not cause further evident N_2O emissions after the initial 28-d monitoring period as majority of the fertilizer-induced N_2O emission flux peaks (39 out of the 49 site-yr-treatments combinations) returned to their baseline levels at the end of the monitoring period.

Grain yields for sidedress N applications were generally greater than those of preplant application at the Ottawa and Guelph sites, with 66 to 75 kg ha^{-1} yield increase for each kg N ha^{-1} applied at sidedress, compared to 46 to 49 kg ha^{-1} yield increase per kg N ha^{-1} for preplant applications. In contrast, grain yields following sidedressing at the Quebec site were similar to those of preplant N treatments (data not shown). In general, the response of grain yield to the applied N fertilizer was quadratic in nature with similar trends for preplant and sidedress application, and grain yields ranged from 6.3 to 10.8 Mg ha^{-1} (Fig. 4b). It most cases, grain yields for 150 or 30+120 kg N ha^{-1} treatments were similar to those of 90 or 30+60 kg N ha^{-1} treatments. Specific N_2O emission [cumulative N_2O emission (g N_2O ha^{-1}) as a function of corn grain yield (Mg ha^{-1}) being produced], increased exponentially from about 20 to 150 g N_2O Mg^{-1} grain with increasing N fertilizer. Sidedress N application always induced 18 to 35 g more N_2O for each tonne of corn grain produced than preplant N (Fig. 4c), likely due to underestimation of the total N_2O emission for the preplant treatment in this cool and humid region.

Conclusion

In this study, our data suggest that the amount of N fertilizer applied affected both the rate and cumulative N_2O emission under corn production in the cool and humid region in eastern Canada. The cumulative N_2O emission ranged from 0.05 to 2.42 kg N ha^{-1}, equivalent to 0.03% to 1.45% of the applied N during the initial 28-d monitoring period after preplant plus a second 28-d monitoring period after sidedress application. Our results indicate that fertilizer application above 90 kg N ha^{-1} will substantially increase N_2O emission without much improvement in yield. The benefit of sidedress N fertilizer in reducing greenhouse gases appears to lie in improved N use efficiency, and the concomitant opportunity to reduce total N rate without yield loss thereby reducing soil N_2O emissions, NO_3^- leaching, and CO_2 emissions for manufacture of N fertilizer. Corn producers are encouraged to adopt optimized fertilizer N management practices with improved N use efficiency, to both maximize economic benefit and minimize N_20 emission and NO_3^- leaching losses.

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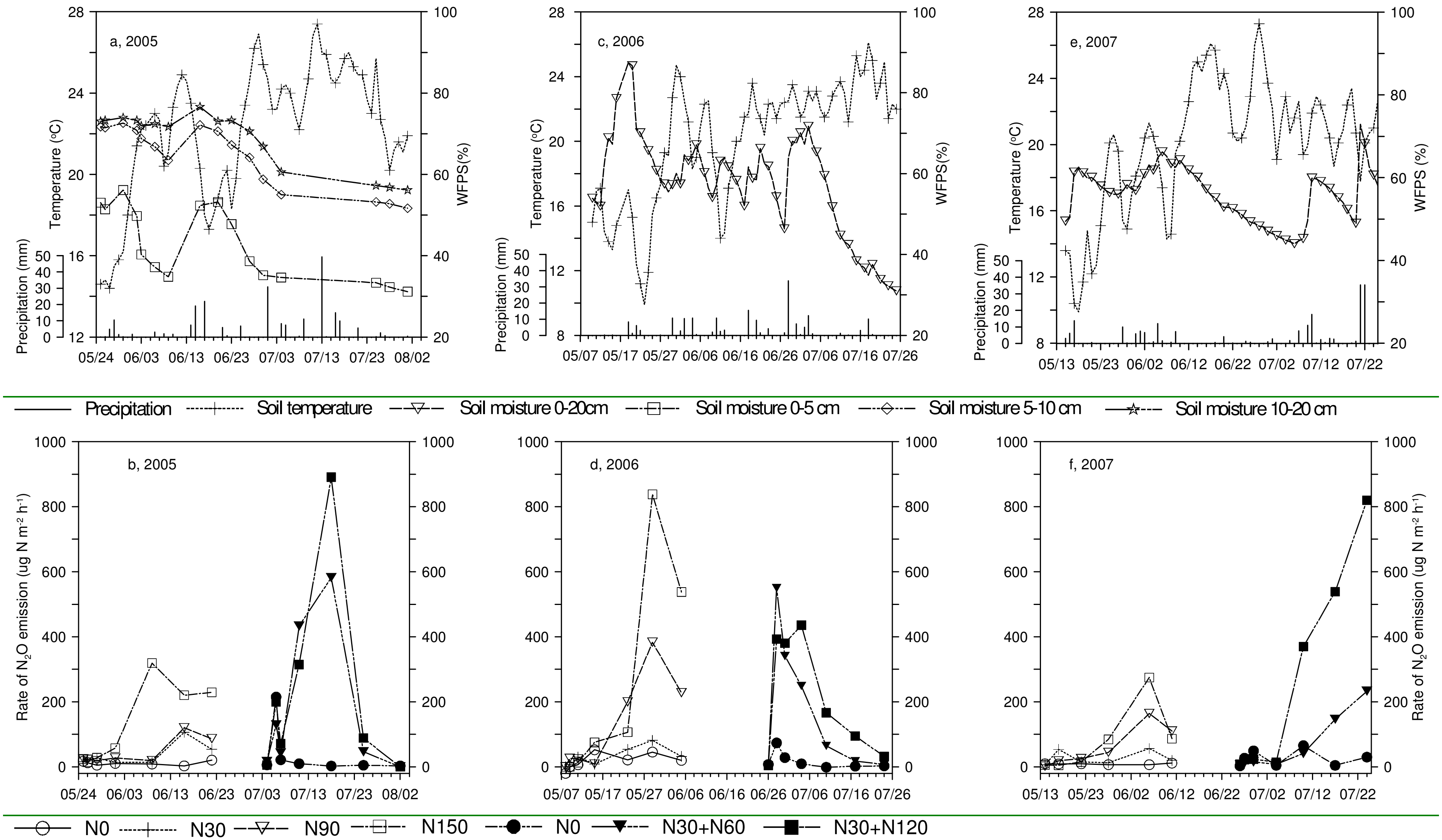

Fig. 1 Precipitation, soil moisture, and soil temperatures during the N_2O monitoring periods, and the means of N_2O emission rate as affected by the amount of preplant or sidedress N at the V6-V8 growth stage at the Ottawa site in 2005 (a, b), 2006 (c, d) and 2007 (e, f).

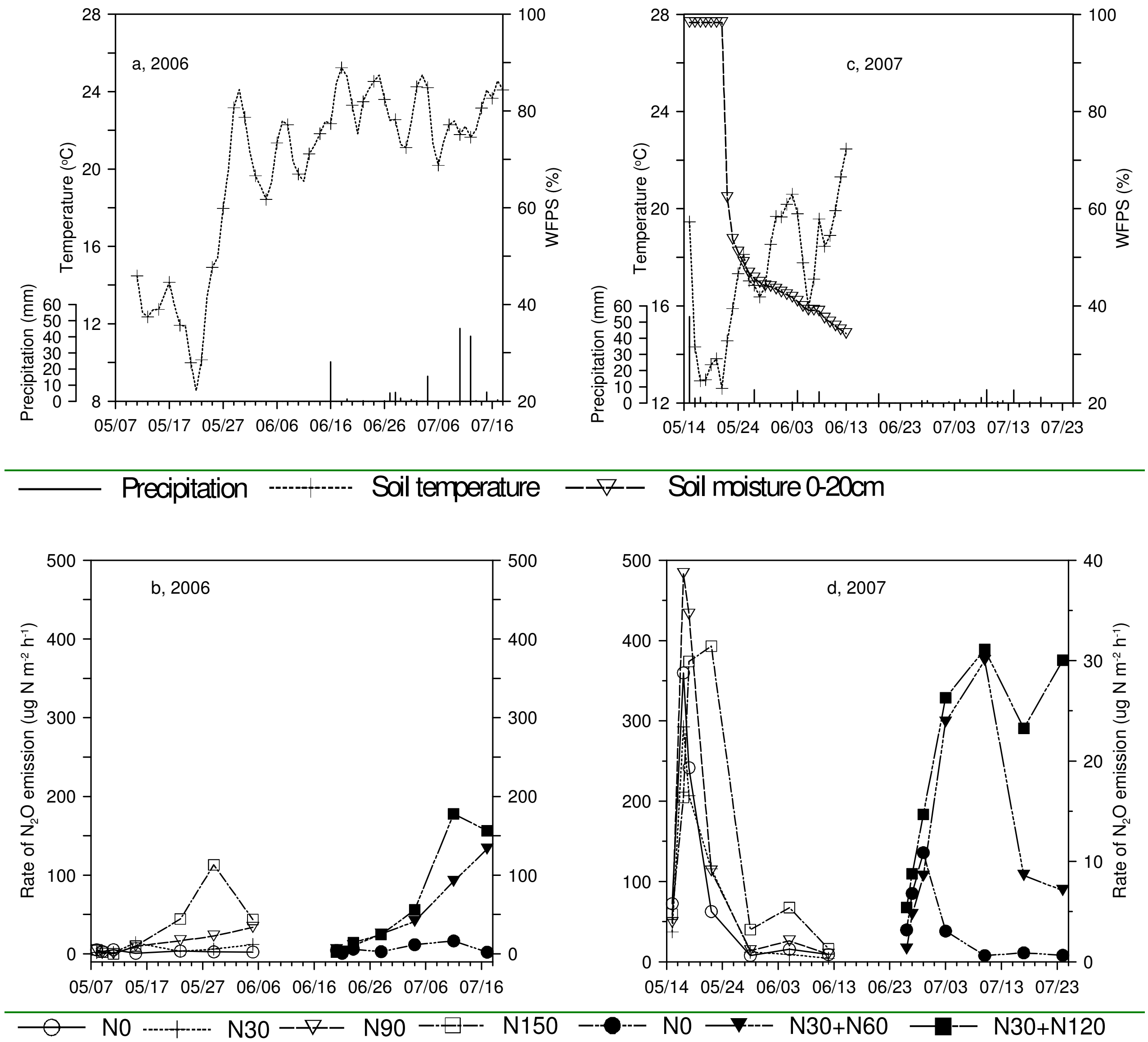

Fig. 2 Precipitation, soil moisture, and soil temperatures during the N_2O monitoring periods, and the means of N_2O emission rate as affected by the amount of preplant or sidedress N at the V6-V8 growth stage at the Guelph site in 2006 (a, b) and 2007 (c, d).

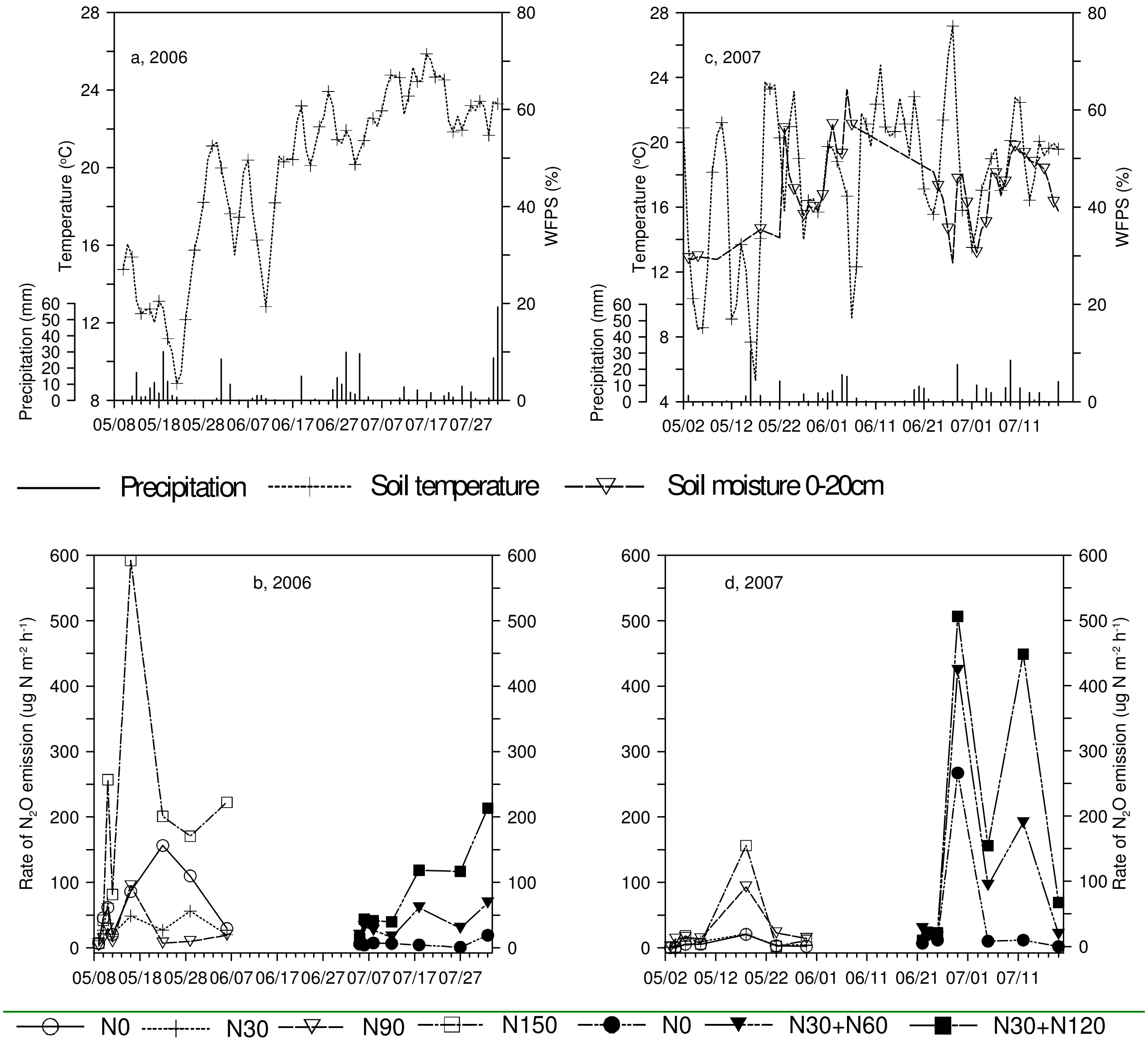

Fig. 3 Precipitation, soil moisture, and soil temperatures during the N_2O monitoring periods, and the means of N_2O emission rate as affected by the amount of preplant or sidedress N at the V6-V8 growth stage at the Saint-Valentin, Quebec site in 2006 (a, b) and 2007 (c, d).

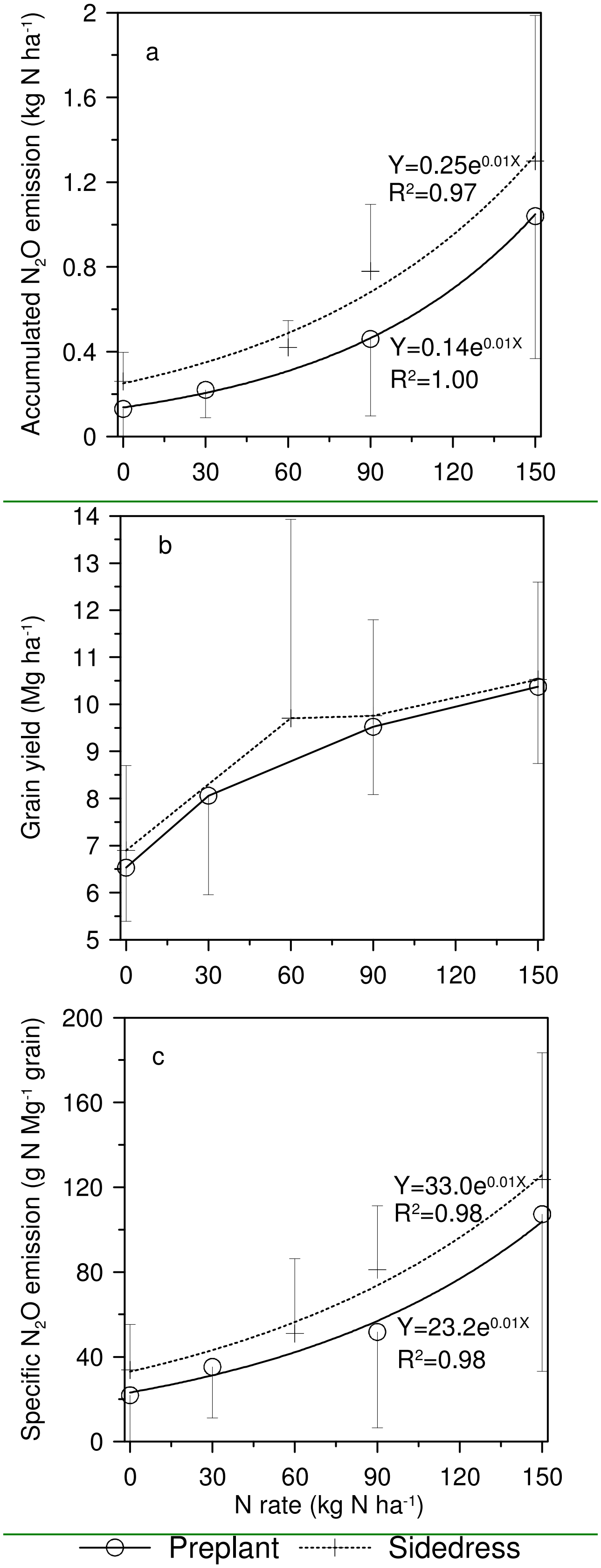
a
Accumulated N2O emission (kg N ha-1)
Y=0.25e0.01X
R2=0.97
Y=0.14e0.01X
R2=1.00
b
Grain yield (Mg ha-1)
c
Specific N2O emission (g N Mg-1 grain)
Y=33.0e0.01X
R2=0.98
Y=23.2e0.01X
R2=0.98
N rate (kg N ha-1)
Preplant
Sidedress

Fig. 4 Cumulative N_2O emission during the 28-d period after fertilization (a), grain yield (b), and specific N_2O emission (c) as affected by the amount of preplant or sidedress N at the V6-V8 growth stage. The vertical bars are the standard error of estimates.