

Supplementary Information

for

Satellite evidence of fertilizer-driven, temperature-dependent ammonia emissions

Mauri Rosiers, Martin Van Damme, Lieven Clarisse, Mark A. Sutton, Camille Viatte, Cathy Clerbaux, Anne-Claude Romain, Pierre Coheur

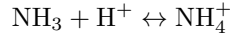
Correspondence: mauri.rosiers@ulb.be

Supplementary Note 1: Mechanistic background on NH_3 volatilization, monotonic parametrizations and urease-limited NH_x supply

This Supplementary Note provides the mechanistic background needed to interpret the main-text satellite results. It summarizes the physicochemical basis of NH_3 volatilization, representative monotonic temperature parametrizations, and the rationale for why urea-dominated systems may depart from monotonic behaviour when NH_x supply depends on in situ urea hydrolysis.

1.1 Physicochemical controls on NH_3 volatilization

NH_3 volatilization is the net upward flux of gaseous NH_3 from soils and vegetation to the atmosphere. In resistance-based formulations, this exchange is controlled by both the thermodynamic potential for NH_3 release from the soil-plant system and the efficiency of transfer to the atmosphere [1, 2]. In soils, NH_3 is in acid-base equilibrium with NH_4^+ :



with

$$K_{\text{NH}_4^+} = \frac{[\text{NH}_3] \cdot [\text{H}^+]}{[\text{NH}_4^+]} \quad (1)$$

Higher pH and warming shift this equilibrium toward free NH_3 , increasing the soil emission potential, commonly expressed as $\Gamma_{\text{soil}} = [\text{NH}_4^+]/[\text{H}^+]$ [3–5]. Dissolved NH_3 can diffuse upward through the liquid phase toward the soil surface, where its release into the atmosphere is governed by Henry’s law (and its constant K_H) [1, 4]:

$$\text{NH}_3(\text{aq}) \leftrightarrow \text{NH}_3(\text{g}), \quad K_H = \frac{[\text{NH}_3]_{\text{aq}}}{p_{\text{NH}_3}} \quad (2)$$

with p_{NH_3} the partial pressure of NH_3 in the gas phase. Under warmer conditions, NH_3 solubility decreases, which further favors volatilization [1, 3, 4]. Soil moisture further modulates this response. High water content favors dissolution and retention of NH_3 in the soil solution, whereas drying can reduce aqueous retention, increase pH through

CO₂ degassing and solute concentration, and enhance transfer to the atmosphere [2, 6–8]. Soil texture, wind speed, background NH₃ concentrations and management also influence exchange. Clay- and silt-rich soils retain NH_x more effectively, whereas sandy soils tend to permit faster pH shifts and sharper emission pulses; wind enhances transfer to the atmosphere, and management controls the size and timing of the NH_x pool available for volatilization [6, 9–11]. Taken together, these physicochemical controls underpin the common expectation that warming strengthens NH₃ volatilization in a strongly non-linear yet broadly monotonic way.

1.2 Representative monotonic NH₃ volatilization parametrizations

Most NH₃ volatilization schemes represent temperature sensitivity through physicochemical partitioning and transfer, and therefore predict a monotonic increase in volatilization with warming [2, 12–16]. A representative canopy compensation-point formulation is given by [2, 17]:

$$\chi(z'_0) = c_T \cdot \frac{[\text{NH}_4^+]}{[\text{H}^+]}, \quad c_T \propto \frac{1}{T} \cdot \exp\left(-\frac{E_a}{RT}\right) \quad (3)$$

where c_T is a temperature-correction factor, $\chi(z'_0)$ approximates the canopy compensation point, R is the gas constant and E_a the effective enthalpy combining the NH₄⁺/NH₃ dissociation and Henry’s law equilibria, with $E_a/R = 10378$ K. In practice, this temperature response is often summarized using terrestrial Q_{10} values of roughly 1.5–3 [2, 17]. Related monotonic temperature corrections have been implemented in chemistry-transport and Earth system models, including ORCHIDEE/CAMEO and AMCLIM, the latter adding explicit roles for water availability, wind and management while retaining a primarily monotonic thermal response when NH_x supply is not limiting [14–16]. A widely used alternative is the exponential temperature correction of Skj  th et al. [12], used to estimate NH₃ emission fluxes (F) from manure and synthetic fertilizer:

$$F \propto T_{\text{corr}} = \exp[0.0223 (T - T_{\text{ref}})] \quad (4)$$

where T is the near-surface (2 m) air temperature (in °C) and T_{ref} a reference temperature. Incorporating this formulation improved the simulation of NH₃ concentrations in the LOTOS–EUROS atmospheric chemistry model [18, 19], while the GEOS-Chem model incorporates a very similar relationship in the MASAGE_NH₃ emission module [20]. Abeed et al. [13] extended this framework to satellite-derived NH₃ total columns:

$$[\text{NH}_3]^{\text{col}} \propto \Gamma_{\text{soil}} \cdot \frac{k \tau}{T_{\text{skin}}} \cdot \exp\left(-\frac{1}{T_{\text{skin}}}\right) \quad (5)$$

where k is an exchange coefficient and τ is the atmospheric lifetime of NH₃. Under sufficiently short lifetimes over agricultural source regions, this provides a rationale for using satellite columns as a proxy for near-surface emission variability [13]. These

schemes are directly relevant to the main-text comparison because they all assume that NH_x supply is not itself constrained by temperature-sensitive biological and enzymatic processes. The main-text results test this assumption observationally. Although a direct quantitative comparison between modelled surface fluxes and satellite-derived NH_3 columns is challenging, because the column signal also reflects retrieval uncertainty, transport, deposition, chemical loss and atmospheric lifetime, it remains useful for testing whether volatilization parameterizations are consistent with long-term observational constraints.

1.3 Why urea-dominated systems may depart from monotonic behaviour

The key distinction for the present study is not total N input, but dominant N form. Non-urea fertilizers supply a substantial fraction of N directly as NH_x or total ammoniacal nitrogen (TAN), so their temperature response is expected to be governed mainly by partitioning and transfer. By contrast, urea-based inputs must first be hydrolyzed to generate the NH_x pool available for volatilization. As urea dominates global synthetic fertilizer use and is also a major form of N in livestock systems, in situ urea hydrolysis exerts broad control on agricultural NH_3 supply [21–23]. This introduces an additional biological step that is largely absent when N is already present in ammoniacal form. A similar distinction applies in livestock systems: fresh excreta deposited directly on soil remain coupled to in situ urease activity, similar to urea-based fertilizers, whereas stored manure is often largely converted to TAN before application and therefore behaves more like a TAN-driven source after spreading, similar to non-urea fertilizers [10, 24–26]. As the main-text classification is based on mineral fertilizer statistics, it does not account for manure or livestock excreta inputs and should therefore be interpreted as a coarse proxy for dominant synthetic fertilizer form rather than total agricultural N input.

1.4 Urease activity, population dynamics and effective field-scale temperature optima

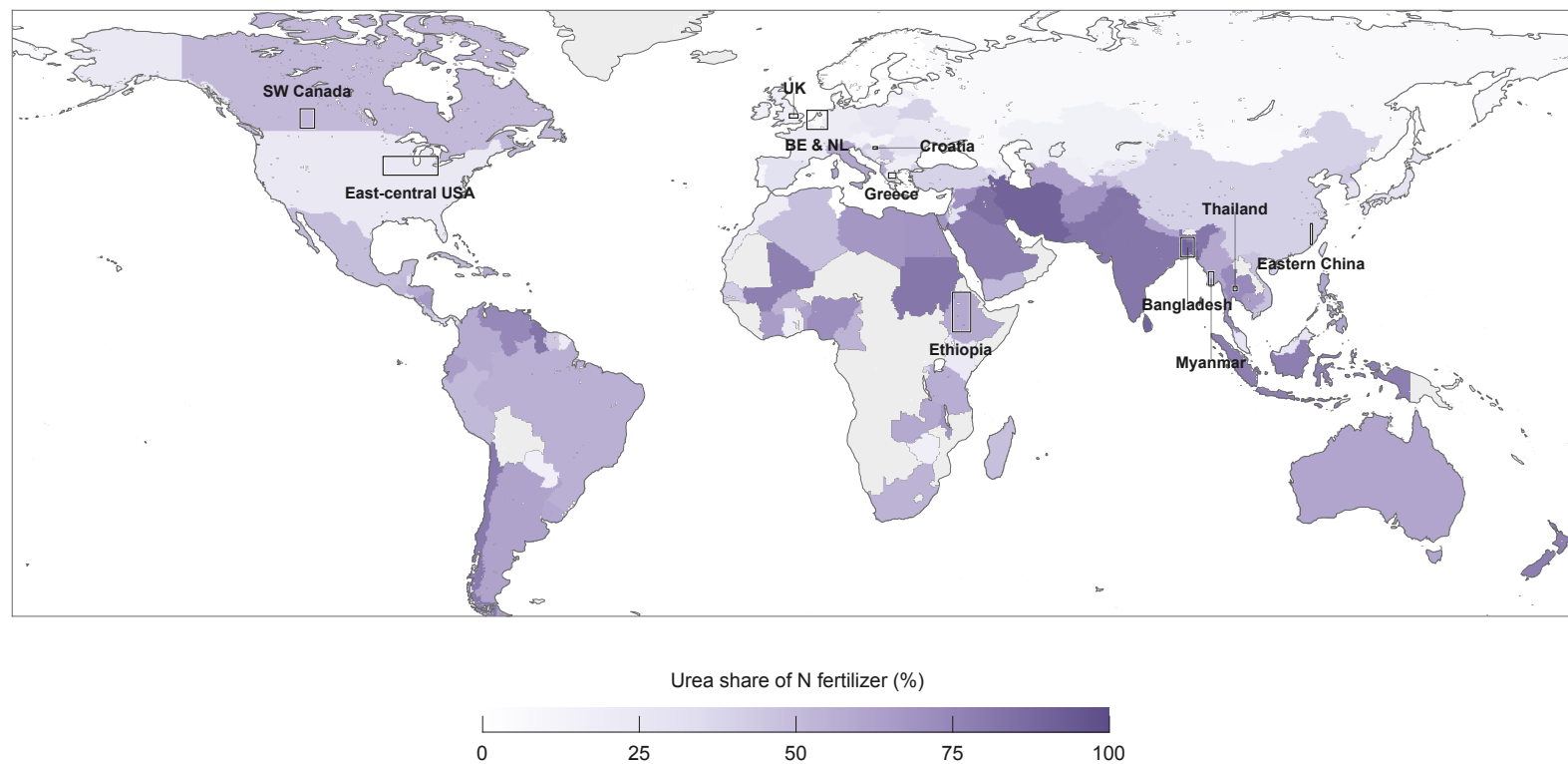
Urease-mediated hydrolysis is the critical step linking urea inputs to NH_x formation. Classical kinetic theory predicts that hydrolysis should accelerate with warming [27–29], but the relevant field-scale response depends not only on instantaneous catalytic efficiency, but also on the abundance, persistence and replenishment of the active urease pool through time [30–32]. This matters because sustained hydrolysis under field conditions is time-integrated: warming can accelerate hydrolysis at first, yet prolonged thermal exposure also accelerates urease inactivation and shortens enzyme persistence [31, 32]. Existing modeling approaches that include temperature-dependent hydrolysis efficiency generally retain a monotonic formulation and do not explicitly represent depletion of the active urease pool [16, 33].

Field-scale hydrolysis capacity also depends on whether biological replenishment can offset enzyme loss. Enzyme persistence declines sharply with temperature: O’Toole and Morgan [34] reported urease half-lives of 384–768 h at 277 K, but only 2–6 h

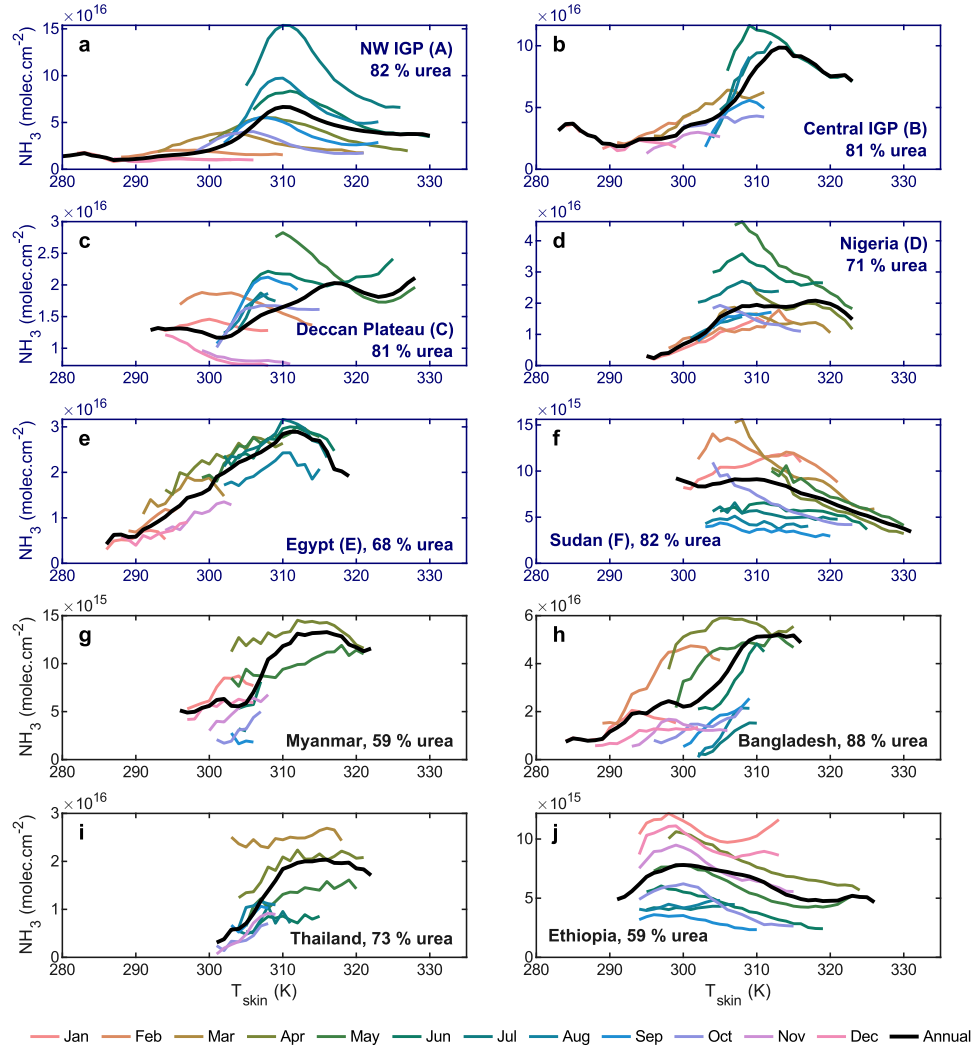
106 at 343 K. Consistent with this, urease synthesis and urease-producing microbial pop-
 107 ulations tend to peak near 303–308 K and decline strongly above ~313 K, so that
 108 losses of active enzyme and microbial biomass may outpace replenishment [32, 35, 36].
 109 Taken together, these mechanisms provide a rationale for an effective field-scale thresh-
 110 old in urea-dominated systems. Under moist, nutrient-rich conditions, warming may
 111 initially enhance catalytic efficiency and support urease production, but beyond a
 112 threshold accelerated enzyme loss can outpace replenishment and reduce the active
 113 urease pool. Under dry or nutrient-limited conditions, this threshold is expected to
 114 shift to lower temperatures as microbial activity and enzyme synthesis weaken [37–39].
 115 This framework motivates the main-text interpretation that the observed breakpoint
 116 in urea-dominated regions is consistent with temperature-limited NH_x supply on field-
 117 relevant timescales, while recognizing that satellite NH_3 columns do not directly
 118 measure urease activity.

119 **Supplementary Note 2: Additional agricultural regions**

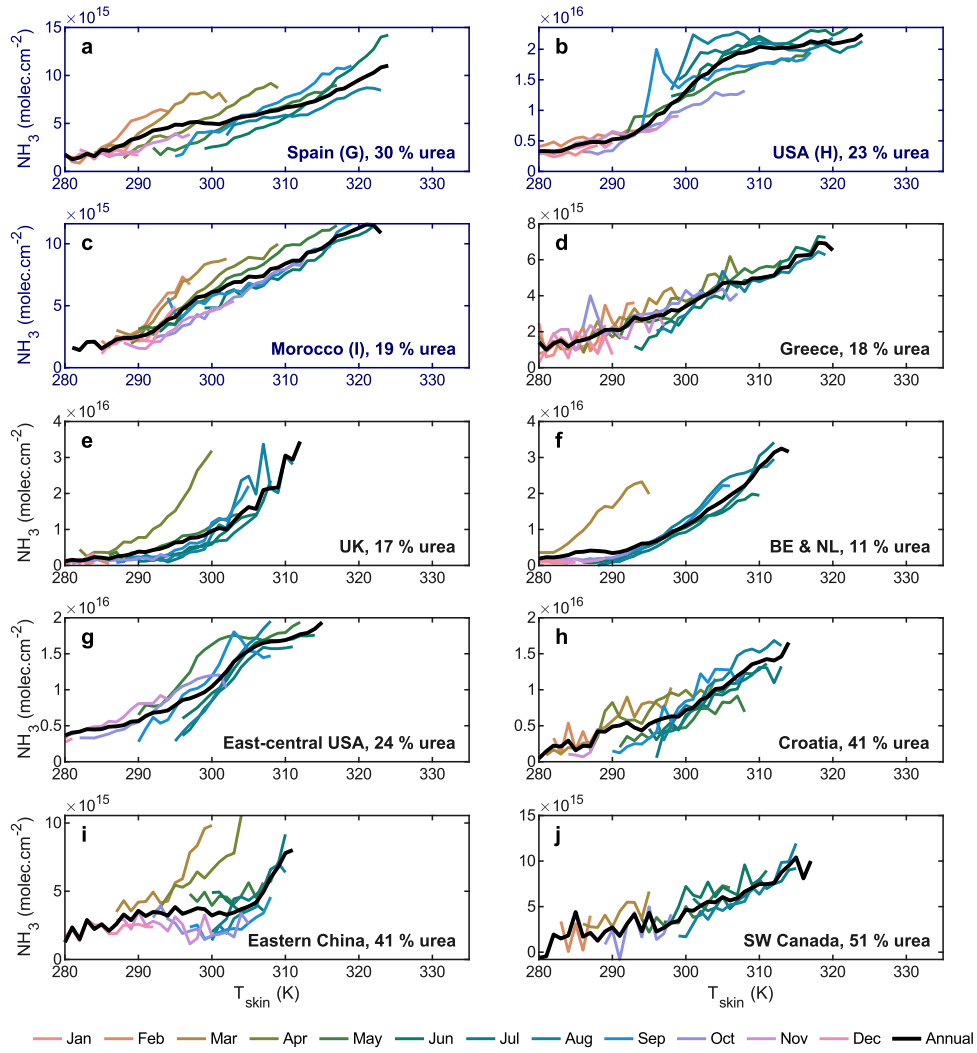
120 To test whether the temperature- NH_3 patterns identified in the nine core regions
 121 are more broadly representative, we analyzed an additional set of agricultural regions
 122 selected solely on the basis of national urea contribution [22]. Whereas the nine core
 123 regions were defined using a deliberately conservative separation (urea $\geq 65\%$ ver-
 124 sus $\leq 40\%$, excluding the intermediate 40–65% range to ensure a clean class contrast;
 125 see Methods), here we relax this criterion to a single 55% split (urea $> 55\%$ ver-
 126 sus $< 55\%$). This intentionally admits intermediate-urea regions that the main-text
 127 selection excluded, providing a broader and deliberately less idealized test of whether
 128 the two response regimes persist beyond the core regions. Supplementary Fig. 1
 129 places these supplementary regions in their global fertilizer context, whereas Supple-
 130 mentary Figs. 2 and 3 show their annual and monthly NH_3 - T_{skin} relationships for
 131 urea-dominated and non-urea dominated systems, respectively. Together with Sup-
 132plementary Table 1, these results provide an independent robustness check of the
 133 main-text interpretation and assess how consistently the two response regimes emerge
 134 beyond the primary case-study regions. For Bangladesh, we lowered the bin-population
 135 threshold from 2% to 0.2% of the most populated bin (Methods). Its most populated
 136 bin holds exceptionally many observations, so the standard 2% rule would remove
 137 its warmest bins even though they are not thinly sampled. With the lower threshold,
 138 every retained bin still holds at least 118 observations, more than the thinnest bins
 139 kept under the standard rule in five other regions.



Supplementary Fig. 1 Country-level fraction (%) of total N fertilizer applied as urea, derived from IFASTAT [22] and aggregated across products and years (2008–2023). Grey areas indicate missing or incomplete data. The black outlines indicate the additional regions selected solely on the basis of urea contribution (> 55% for urea-dominated regions; Supplementary Fig. 2, and < 55% for non-urea dominated regions; Supplementary Fig. 3).



Supplementary Fig. 2 Annual and monthly mean NH_3 – T_{skin} relationships for agricultural regions worldwide with a urea contribution > 55%. Regions of interest (ROIs), as defined in Fig. 1 of the main text, are shown in dark blue, while additional regions are shown in black, consistent with Supplementary Fig. 1.



Supplementary Fig. 3 Annual and monthly mean NH_3 – T_{skin} relationships for agricultural regions worldwide with a urea contribution < 55%. Regions of interest (ROIs), as defined in Fig. 1 of the main text, are shown in dark blue, while additional regions are shown in black, consistent with Supplementary Fig. 1.

Supplementary Table 1 The eleven additional regions of Supplementary Figures 2 and 3. Columns as in Table 1; bracketed values are the range across the calendar months, each fitted separately; where only one month satisfies the reporting criteria, no range is given, and as in Table 1 the annual value does not need to fall within the monthly range. Regions are ordered by urea contribution and grouped by a single threshold at 55 % urea share, rather than the 65 %/40 % criterion used for the nine focus regions of the main text.

Region (Soil Type)	Urea	Q_{10}	T_b
<i>Urea-dominated (≥ 55 % urea)</i>			
Bangladesh (clayey soil)	87.5%	1.81 (1.26–3.68)	— ^a (293–298 K)
Thailand (clayey soil)	72.7%	— ^b	—
Myanmar (clayey soil)	59.4%	1.95 (1.23–1.41)	—
Ethiopia (clayey soil)	59.3%	1.52	300 K (299–300 K)
<i>Non-urea-dominated (< 55 % urea)</i>			
SW Canada (silty soil)	51.0%	1.73 (1.60–2.53)	—
Croatia (silty soil)	41.4%	2.01 (2.15–2.43)	—
Eastern China (silty soil)	40.6%	1.28 (1.96–2.15)	—
East-central USA (silty soil)	23.6%	1.76 (1.57–4.37) ^c	—
Greece (silty soil)	18.5%	1.61 (1.48–2.38)	—
United Kingdom (clayey soil)	16.5%	2.77 (3.14–5.19) ^c	—
Belgium & Netherlands (silty soil)	11.1%	2.42 (4.37–5.11) ^c	—

^aNo annual T_b : the column flattens above 310 K but never declines within the reported range, so no turnover is resolved (Methods). Two individual months do turn over and are listed in Supplementary Table 2. ^bSampling too sparse for a quantitative Q_{10} ; the shape of the response is reported qualitatively only (Methods). ^cThe monthly Q_{10} values in these three regions rise above what the compensation-point thermodynamics of Fig. 2 of the main text can produce over the same temperature range. The months involved are those of the growing season, June to September, with March in addition in Belgium and the Netherlands and August alone in East-central USA. In north-west Europe, these are the most agriculturally active months, spanning the start of the growing season in March and the grazing and application season that follows [12, 13]. These elevated slopes could possibly be linked to the timing of application rather than to the temperature sensitivity of a standing nitrogen pool. The annual values, fitted across the full temperature range, remain below the thermodynamic ceiling.

Supplementary Table 2 Calendar months in which the NH_3 column turns over, and the temperature at which it does so. A month contributes where its own curve rises into a maximum, then declines and stays down over the remainder of its sampled range, the same criteria applied to the annual curves of Table 1. Months absent either never turn over within their sampled range or decline across all of it. T_b rises through the season wherever enough months resolve one, and in the Northwest Indo-Gangetic Plain the months with a higher T_b also reach a higher NH_3 maximum ($r = 0.90$ between T_b and the logarithm of the monthly maximum, eight months spanning 13 K). Both are expected if the size of the ammoniacal nitrogen pool sets the turnover.

Region	Months with a turnover (T_b , K)	n
NW IGP	Feb 298, Mar 302, Apr 308, Jun 311, Jul 310, Aug 310, Sep 307, Oct 306	8
Ethiopia	May 300, Oct 300, Nov 299, Dec 299	4
Sudan	Jun 311, Jul 307, Aug 307	3
Central IGP	Jun 309, Dec 294	2
Nigeria	Mar 307, Jun 308	2
Bangladesh	Jan 293, Nov 298	2
Egypt	Jul 310	1
Deccan Plateau	Feb 299	1
Myanmar	Apr 312	1

Supplementary Table 3 Bounding boxes and sampling of the twenty analyzed regions. Longitude and latitude limits of each rectangular box in degrees (Methods), the number of 1/12° grid cells within it that pass the 40 % cropland criterion, and the number of quality-filtered morning IASI observations that enter the binned annual curve over 2008–2023, after exclusion of the region-specific fire months and of bins failing the population threshold (Methods). The nine regions of the main text are listed first, in the order of Table 1; the eleven additional regions follow, ordered by urea contribution as in Supplementary Table 1.

Region	Longitude	Latitude	Cells	IASI obs.
<i>Main text (Fig. 1, Table 1)</i>				
NW IGP (A)	69.12 to 74.54	25.15 to 33.50	3266	2 205 899
Central IGP (B)	79.38 to 82.96	26.71 to 27.54	385	88 939
Deccan Plateau (C)	73.87 to 80.60	15.45 to 24.60	8030	2 518 691
Nigeria (D)	7.13 to 9.79	11.38 to 12.96	503	167 293
Egypt (E)	30.40 to 31.85	30.41 to 31.20	147	56 026
Sudan (F)	32.46 to 35.54	11.63 to 14.54	936	428 620
Spain (G)	−7.27 to −3.60	37.86 to 40.03	798	298 407
USA (H)	−102.38 to −97.38	37.54 to 39.88	1324	404 131
Morocco (I)	−7.20 to −4.46	33.06 to 35.84	570	274 600
<i>Supplementary Figs. 2 and 3</i>				
Bangladesh	88.40 to 91.45	22.05 to 26.26	1247	295 690
Thailand	100.38 to 101.29	14.79 to 15.79	113	24 003
Myanmar	94.70 to 95.96	16.02 to 18.91	370	98 460
Ethiopia	35.93 to 40.11	6.00 to 14.50	2951	1 441 505
SW Canada	−113.88 to −110.54	49.71 to 53.88	1757	4 833
Croatia	17.70 to 18.70	45.20 to 45.75	64	15 473
Eastern China	118.10 to 118.60	24.75 to 29.25	6	47 951
East-central USA	−94.84 to −82.22	39.63 to 43.65	6030	1 111 979
Greece	21.25 to 22.97	38.96 to 40.13	79	59 460
United Kingdom	−1.54 to 0.46	51.88 to 52.79	223	26 793
Belgium & Netherlands	2.50 to 7.25	49.45 to 53.55	1118	251 293

References

- [1] Sutton, M. A., Asman, W. A. H. & Schjørring, J. K. Dry deposition of reduced nitrogen. *Tellus B* **46**, 255–273 (1994).
- [2] Sutton, M. A. *et al.* Towards a climate-dependent paradigm of ammonia emission and deposition. *Philosophical Transactions of the Royal Society B: Biological Sciences* **368**, 20130166 (2013).
- [3] Roelle, P. A. & Aneja, V. P. Modeling of ammonia emissions from soils. *Environmental Engineering Science* **22**, 58–72 (2005).
- [4] Roelle, P. A. & Aneja, V. P. Characterization of ammonia emissions from soils in the upper coastal plain, North Carolina. *Atmospheric Environment* **36**, 1087–1097 (2002).
- [5] Générmont, S. & Cellier, P. A mechanistic model for estimating ammonia volatilization from slurry applied to bare soil. *Agricultural and Forest Meteorology* **88**, 145–167 (1997).
- [6] Krichels, A. H. *et al.* Soil NH₃ emissions across an aridity, soil pH, and N deposition gradient in southern California. *Elementa: Science of the Anthropocene* **11**, 00123 (2023).
- [7] Sommer, S. G. & Hutchings, N. J. Ammonia emission from field applied manure and its reduction—invited paper. *European Journal of Agronomy* **15**, 1–15 (2001).
- [8] Pelster, D. *et al.* Can soil clay content predict ammonia volatilization losses from subsurface-banded urea in eastern Canadian soils? *Canadian Journal of Soil Science* **98**, 556–565 (2018).
- [9] Rochette, P. *et al.* Banding of urea increased ammonia volatilization in a dry acidic soil. *Journal of Environmental Quality* **38**, 1383–1390 (2009).
- [10] Sommer, S., Schjørring, J. & Denmead, O. Ammonia emission from mineral fertilizers and fertilized crops. *Advances in Agronomy* **82**, 557–622 (2004).
- [11] Behera, S. N., Sharma, M., Aneja, V. P. & Balasubramanian, R. Ammonia in the atmosphere: a review on emission sources, atmospheric chemistry and deposition on terrestrial bodies. *Environmental Science and Pollution Research* **20**, 8092–8131 (2013).
- [12] Skjøth, C. A., Hertel, O., Gyldenkerne, S. & Ellermann, T. Implementing a dynamical ammonia emission parameterization in the large-scale air pollution model ACDEP. *Journal of Geophysical Research: Atmospheres* **109**, D06306 (2004).

- [13] Abeed, R. *et al.* A roadmap to estimating agricultural ammonia volatilization over Europe using satellite observations and simulation data. *Atmospheric Chemistry and Physics* **23**, 12505–12523 (2023).
- [14] Beaudor, M. *et al.* Global agricultural ammonia emissions simulated with the ORCHIDEE land surface model. *Geoscientific Model Development* **16**, 1053–1081 (2023).
- [15] Vira, J., Hess, P., Melkonian, J. & Wieder, W. R. An improved mechanistic model for ammonia volatilization in Earth system models: Flow of agricultural nitrogen version 2 (FANv2). *Geoscientific Model Development* **13**, 4459–4490 (2020).
- [16] Jiang, J., Stevenson, D. S. & Sutton, M. A. A dynamical process-based model for quantifying global agricultural ammonia emissions – AMmonia–CLIMate v1.0 (AMCLIM v1.0) – part 1: Land module for simulating emissions from synthetic fertilizer use. *Geoscientific Model Development* **17**, 8181–8222 (2024).
- [17] Nemitz, E., Sutton, M. A., Schjoerring, J. K., Husted, S. & Paul Wyers, G. Resistance modelling of ammonia exchange over oilseed rape. *Agricultural and Forest Meteorology* **105**, 405–425 (2000).
- [18] Hendriks, C. *et al.* Ammonia emission time profiles based on manure transport data improve ammonia modelling across north western Europe. *Atmospheric Environment* **131**, 83–96 (2016).
- [19] Manders, A. *et al.* Curriculum vitae of the LOTOS–EUROS (v2.0) chemistry transport model. *Geoscientific Model Development* **10**, 4145–4173 (2017).
- [20] Paulot, F. *et al.* Ammonia emissions in the United States, European Union, and China derived by high-resolution inversion of ammonium wet deposition data: Interpretation with a new agricultural emissions inventory (MASAGE_NH3). *Journal of Geophysical Research: Atmospheres* **119**, 4343–4364 (2014).
- [21] Cantarella, H., Otto, R., Soares, J. R. & Silva, A. G. d. B. Agronomic efficiency of NBPT as a urease inhibitor: A review. *Journal of Advanced Research* **13**, 19–27 (2018).
- [22] International Fertilizer Association. Global consumption of synthetic nitrogen fertilizers per country (2024). URL <https://www.ifastat.org/databases/plant-nutrition>.
- [23] Penuelas, J., Coello, F. & Sardans, J. A better use of fertilizers is needed for global food security and environmental sustainability. *Agriculture & Food Security* **12**, 5 (2023).
- [24] Misselbrook, T. H. *et al.* Crusting of stored dairy slurry to abate ammonia emissions. *Journal of Environmental Quality* **34**, 411–419 (2005).

- 210 [25] Misselbrook, T. H., Webb, J. & Gilhespy, S. L. Ammonia emissions from outdoor
211 concrete yards used by livestock—quantification and mitigation. *Atmospheric*
212 *Environment* **40**, 6752–6763 (2006).
- 213 [26] Prasad, C. S., Anandan, S., Gowda, N. K. S., Schlecht, E. & Buerkert, A. Man-
214 aging nutrient flows in Indian urban and peri-urban livestock systems. *Nutrient*
215 *Cycling in Agroecosystems* **115**, 159–172 (2019).
- 216 [27] Eyring, H. The activated complex in chemical reactions. *The Journal of Chemical*
217 *Physics* **3**, 107–115 (1935).
- 218 [28] Laidler, K. J. & King, M. C. Development of transition-state theory. *The Journal*
219 *of Physical Chemistry* **87**, 2657–2664 (1983).
- 220 [29] Truhlar, D. G., Garrett, B. C. & Klippenstein, S. J. Current status of transition-
221 state theory. *The Journal of Physical Chemistry* **100**, 12771–12800 (1996).
- 222 [30] Arcus, V. L. *et al.* On the temperature dependence of enzyme-catalyzed rates.
223 *Biochemistry* **55**, 1681–1688 (2016).
- 224 [31] Daniel, R. M. & Danson, M. J. Temperature and the catalytic activity of enzymes:
225 A fresh understanding. *FEBS Letters* **587**, 2738–2743 (2013).
- 226 [32] Feder, M. J., Akyel, A., Morasko, V. J., Gerlach, R. & Phillips, A. J. Temperature-
227 dependent inactivation and catalysis rates of plant-based ureases for engineered
228 biomineralization. *Engineering Reports* **3**, e12299 (2021).
- 229 [33] Riddick, S. N. *et al.* High temporal resolution modelling of environmentally-
230 dependent seabird ammonia emissions: Description and testing of the GUANO
231 model. *Atmospheric Environment* **161**, 48–60 (2017).
- 232 [34] O’Toole, P. & Morgan, M. A. Thermal stabilities of urease enzymes in some Irish
233 soils. *Soil Biology and Biochemistry* **16**, 471–474 (1984).
- 234 [35] Mekonnen, E., Kebede, A., Nigussie, A., Kebede, G. & Tafesse, M. Isolation
235 and characterization of urease-producing soil bacteria. *International Journal of*
236 *Microbiology* **2021**, 8888641 (2021).
- 237 [36] Manna, S., Dutta, S., Kumar, M., Panwar, A. & Roy, D. Urease-driven CaCO_3
238 production by *Bacillus megaterium* RB-05 for application in sand stabilization.
239 *Biologia* **79**, 2907–2915 (2024).
- 240 [37] Steinweg, J. M., Dukes, J. S., Paul, E. A. & Wallenstein, M. D. Microbial
241 responses to multi-factor climate change: effects on soil enzymes. *Frontiers in*
242 *Microbiology* **4**, 146 (2013).
- 243 [38] Schimel, J. P., Becerra, C. A. & Blankinship, J. C. Estimating decay dynamics for
244 enzyme activities in soils from different ecosystems. *Soil Biology and Biochemistry*

245 **114**, 5–11 (2017).

246 [39] Feng, T. *et al.* Soil urease activity is mediated more by *ureC* microbial diversity in
247 wet regions than dry regions: Key roles of generalist-abundant and -rare species.
248 *Functional Ecology* **39**, 2015–2028 (2025).