Land Use Specific Ammonia Deposition Velocities: a Review of Recent Studies (2004–2013)

Frederik Schrader · Christian Brümmer

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Abstract Land use specific deposition velocities of atmospheric trace gases and aerosols—particularly of reactive nitrogen compounds—are a fundamental input variable for a variety of deposition models. Although the concept is known to have shortcomings—especially with regard to bi-directional exchange—the often limited availability of concentration data and meteorological input variables make it a valuable simplification for regional modeling of deposition fluxes. In order to meet the demand for an up-to-date overview of recent publications on measurements and modeling studies, we compiled a database of ammonia (NH₃) deposition velocities published from 2004 to 2013. Observations from a total of 42 individual studies were averaged using an objective weighing scheme and classified into seven land use categories. Weighted average and median deposition velocities are 2.2 and 2.1 cm s⁻¹ for coniferous forests, 1.5 and 1.2 cm s⁻¹ for mixed forests, 0.9 and 0.7 cm s⁻¹ for deciduous forests, 0.7 and 0.6 cm s⁻¹ for semi-natural sites, 0.7 and 0.8 cm s⁻¹ for urban sites, 0.7 and 0.6 cm s⁻¹ for water surfaces, and 1.0 and 0.4 cm s⁻¹ for agricultural sites, respectively. Thus, values presented in this compilation were considerably lower than those found in former studies (e.g., VDI 2006). Reasons for the mismatch were likely due to different land use classification, different averaging methods, choices of measurement locations, and improvements in measurement and in modeling techniques. Both data and code used for processing are made available as supplementary material to this article.

Keywords NH₃ · Ammonia · Deposition velocity · Review

1 Introduction

Atmospheric ammonia (NH₃) has long been recognized as a major airborne pollutant. It can act as a precursor for aerosols, and its deposition has a significant impact on soil acidification, ecosystem eutrophication and, consequently, changes in species composition and biodiversity (Sutton et al. 2011). In order to assess the impact of ammonia emissions and transport, mainly caused by livestock and fertilization (Bouwman et al. 1997), some air quality models (e.g., the AUSTAL2000 model of Janicke 2002) use a so-called inferential method; that is, the deposition flux \( F \) (g m⁻² s⁻¹) is calculated as the product of the concentration of a compound at a certain reference height, \( c_{zR} \) (µg m⁻³), and a proportionality constant, the deposition velocity \( v_d \) (cm s⁻¹) (Wesely and Hicks 2000). In addition, land use specific average deposition velocities may be used for quick estimates of N deposition to an ecosystem, or to verify plausibility of flux measurements and model results.

Conceptually, using tabulated deposition velocities for a certain land use category is based on strongly simplified assumptions about the relationship between near-ground NH₃ concentrations and the respective deposition flux; however, for now, this simplification is
still often necessary once we leave the single plot scale. The deposition of NH₃ involves a large number of complex processes, especially due to the high reactivity of the compound, strong water solubility, formation of particulate matter in the form of ammonium nitrate (NH₄NO₃) in the presence of nitric acid (HNO₃), bi-directional transport paths and canopy-dependent compensation points, non-stomatal uptake, co-deposition of NH₃ and SO₂, and other factors (Sutton et al. 2007, 2011; Flechard et al. 2013). In practice, it is not always possible to resolve these processes in regional models, primarily due to limited availability of spatial input data. In the recent past, many formulations for bi-directional, compensation point based dry deposition models have arisen in the literature (Bajwa et al. 2008; Neiryck and Ceulemans 2008; Personne et al. 2009; Massad et al. 2010; Zhang et al. 2010). However, necessary input parameters for these models may not always be available for larger areas. Therefore, many of these processes and characteristics are sometimes aggregated in a single reference value of the deposition velocity per land use type. For example, in Germany, a set of three reference values compiled by the Association of German Engineers (Verein Deutscher Ingenieure, VDI) based on data from 10 years ago and earlier (VDI 2006) is commonly used in regional model applications.

The ongoing intensification of agricultural practices, as well as increasing traffic volume and industrial processes, calls for a periodic update of these land use specific values. Furthermore, flux measurement and modeling techniques have greatly improved, and a number of large monitoring studies were carried out in the last few years. Measurements covered by this literature study were carried out using a number of different methods, including the aerodynamic gradient technique (Phillips et al. 2004), relaxed eddy accumulation (Meyers et al. 2006), chamber methods (Jones et al. 2007), and N deposition estimation using biomonitoring (Russow and Weigel 2000; Weigel et al. 2000; Russow and Bohme 2005; Sommer et al. 2009; Tauchnitz et al. 2010) or synthetic surrogate surfaces (Anatolaki and Tsitouridou 2007). Additionally, inferential (Hicks et al. 1987; Wesely and Hicks 2000) and chemical transport models (Builtjes et al. 2011) were used to simulate deposition fluxes. The aim of this study is to incorporate these new measurement and model approaches into an up-to-date database of ammonia deposition velocities published in the preceding decade. These are presented in a generalized form as weighted annual averages and median values for different land use types. Both the data and IPython code that was used for the calculation of these new reference numbers are published as supplementary material of this article for re-use and modification by other researchers.

### 2 Materials and Methods

#### 2.1 Literature Survey

We performed an iterative, snowball-type literature research: In a first step, the citation indexing service Thomson Reuters Web of Science (formerly ISI Web of Knowledge) was queried using they keywords \textit{ammonia+deposition+veloc*}. Search results were limited to the period from 2004 to 2013. The query yielded a total of 90 international publications, which were then screened for obviously unrelated articles, e.g., such articles that only deal with the deposition velocity of other trace gases in detail. We only used sources in our further analysis that either directly report measured, modeled, or otherwise researched deposition velocities or that include measurements of deposition fluxes and corresponding NH₃ concentrations that could be used to calculate deposition velocities. Consequently, studies that only discuss the concept of deposition velocities in general were disregarded. All sources were reviewed for (i) measurement method, (ii) NH₃ deposition velocities (directly reported, or calculated by the authors of this article), (iii) reference height, (iv) NH₃ concentrations at the reference height, (v) descriptions of the measurement site and land use, and (vi) temporal coverage (how many seasons do the measurements cover and how long did the authors measure during these respective seasons). In a second step, the references cited in the results from the initial database query were screened for further potentially useful articles published in the time frame of interest. These were then again treated as described above and likewise screened for further
relevant studies. This process was repeated until no additional literature could be obtained. In the end, this approach led to a collection of 42 suitable sources that were used for statistical analysis and classification into different land use types.

2.2 Data Processing

Most of the studies cited here report their findings on NH3 deposition velocities either directly in the text or as tabulated values. If in the studies cited NH3 deposition velocity values were not directly reported in the text or in tables, we determined \( v_d \) from deposition fluxes and concentrations at the reference height. In a few studies, \( v_d \) could only be visually estimated from figures. In those cases when only a range of measured deposition velocities was reported, the center of this range was taken as an estimate for the average deposition velocity for the respective site. When multiple values of \( v_d \) were reported, e.g., as a result of data syntheses, modeling studies, or literature surveys, these were grouped by land use class, arithmetically averaged, and used as a single study in the further analysis.

The results were categorized into seven land use classes: deciduous-, coniferous-, and mixed forests, semi-natural sites (e.g., grasslands or peatlands), urban sites, agricultural sites, and water surfaces. Studies were classified as unspecified when the site description was unclear (e.g., remote site) or when deposition velocities were reported as one for multiple land use categories. Two statistics were calculated as a means of aggregation: the median, as a robust estimator for the central tendency, and a weighted average of the respective groups.

The former was calculated as follows:

\[
\tilde{v}_d = \begin{cases} 
  v_{d,\frac{n}{2}+1}, & \text{if } n \text{ is odd}, \\
  \frac{1}{2} \left(v_{d,\frac{n}{2}} + v_{d,\frac{n}{2}+1}\right), & \text{if } n \text{ is even},
\end{cases}
\]

where \( \tilde{v}_d \) (cm s\(^{-1}\)) is the median deposition velocity of one land use class and \( v_{d,i} \) (cm s\(^{-1}\)) is the deposition velocity at the \( i \)th position of a sorted array of \( v_d \) for the respective category.

Weights for the latter were derived from the temporal coverage of the corresponding studies: For each season (i.e., spring, summer, fall, and winter) of the year where the measurements were conducted (regardless of the number of years), a study was assigned one point, as well as additional points for the measurement duration during these seasons (i.e., 0 to 3 weeks of a season: one point; 3 to 6 weeks: two points, 6 to 9 weeks: three points, 9 weeks and more: four points). Consequently, each study would be weighted with a minimum of two points (1 day to 3 weeks of measurement during one season) and a maximum of eight points (average of 9 weeks of measurements or more for each of four seasons). The weighted average deposition velocity for one land use class \( v_d \) (cm s\(^{-1}\)) was then calculated by multiplication of the individual studies’ \( v_{d,i} \) with the weights for the number of seasons \( w_{s,i} \) and the coverage of these seasons \( w_{c,i} \) (−) and division by the total sum of weights assigned for all \( v_{d,i} \) of one land use class:

\[
\bar{v}_d = \frac{\sum_{i=1}^{n} \left( v_{d,i} w_{c,i} + v_{d,i} w_{s,i} \right)}{\sum_{i=1}^{n} \left( w_{c,i} + w_{s,i} \right)}.
\]

3 Results

A total of 42 studies were deemed relevant and reliable and were, except for two duplicate values (Neirynck et al. 2005, 2007; Neirynck and Ceulemans 2008), consequently used in the calculation of average and median \( v_d \) for the seven land use classes. Since a subset of these studies were compilations of results from large measurement campaigns, or literature studies themselves, a higher number (61) of individual values for the ammonia deposition velocity could be extracted. Only one value per land use class (if based on the same measurement technique) of an individual study was used in the averaging process; some studies, such as Flechard et al. (2011), are actually based on data syntheses from more than 50 sites. Broken down into land use classes, we were able to use six, four, four, 19, five, three, 18, and two individual values for coniferous forests, mixed forests, deciduous forests, semi-natural sites, urban sites, water surfaces, agricultural sites, and unspecified sites, respectively (Table 1). Studies conducted at semi-natural and agricultural sites were clearly found to be dominant.
Median deposition velocities were highest for coniferous forests and lowest for agricultural sites. Weighted averages show a slightly different order, with the highest values again from coniferous forest sites, but the lowest from urban sites and water surfaces (Fig. 1).

While many studies (75%) covered all four seasons, 18% of all studies only measured during one season. Two thirds of $v_d$ values are based on continuous measurements; however, 21 and 11% of all studies only covered up to 3 or up to 6 weeks per season, respectively.

Table 1 Medians, weighted averages, and ranges of ammonia deposition velocities categorized by land use

| Land use        | $n$ (−) | Min | Max | Median | Weighted avg |
|-----------------|---------|-----|-----|--------|--------------|
| Coniferous forest | 6       | 0.5 | 3.3 | 2.1    | 2.2          |
| Mixed forest    | 4       | 0.4 | 3.0 | 1.2    | 1.5          |
| Deciduous forest| 4       | 0.3 | 1.8 | 0.9    | 1.1          |
| Semi-natural    | 19      | 0.1 | 1.8 | 0.7    | 0.9          |
| Urban           | 5       | 0.1 | 1.1 | 0.8    | 0.7          |
| Water           | 3       | 0.5 | 0.9 | 0.6    | 0.7          |
| Agricultural    | 18      | 0.2 | 7.1 | 0.4    | 1.0          |
| Unspecified     | 2       |     |     |        |              |

$n$ is the number of individual data for each category

4 Discussion and Concluding Remarks

We presented a compilation of ammonia deposition velocities (Table 2 in the Appendix) as a function of land use based on measurements, modeling studies, and literature survey results from the period 2004 to 2013. In total, 61 individual $v_d$ values (not including duplicates) were extracted from 42 studies. Two studies were omitted because they appeared to be reanalysis studies of the same data set, and two values could not unambiguously be attributed to a specific land use class.

Staelens et al. (2012) compiled a literature review of deposition velocities for NH$_3$, NO$_2$, and SO$_2$ from the period 1972 to 2006. They report $v_d$ of 1.14 cm s$^{-1}$ (min 0.65, max 1.71, $n=7$) for grassland and 1.56 cm s$^{-1}$ (min 0.80, max 2.20, $n=6$) for heathland, both thereby slightly higher but in the same range as our figure for semi-natural ecosystems of 0.9 cm s$^{-1}$ (median 0.7, min 0.1, max 1.8, $n=19$). Their average numbers for deciduous forests, 1.54 cm s$^{-1}$ (min 0.81, max 2.20, $n=4$), and coniferous forests, 2.91 cm s$^{-1}$ (min 2.00, max 3.80, $n=12$), are likewise higher than ours of 1.1 cm s$^{-1}$ (median 0.9, min 0.3, max 1.8, $n=4$) and 2.2 cm s$^{-1}$ (median 2.1, min 0.5, max 3.3, $n=6$) for deciduous and coniferous forests, respectively. The Association of German Engineers (VDI 2006) reports a deposition velocity of 1.5 cm s$^{-1}$ for grass and 2.0 cm s$^{-1}$ for forests, which is, again, slightly higher, but not inconsistent with our
findings. Reasons for the mismatch might be the specific choices of categories for aggregation and the averaging procedure. In addition, one may want to calculate individual metrics for central tendency, e.g., a truncated mean, a weighted median, or include outlier corrections, e.g., for the agricultural data set. Therefore, all data used in this study are made available as supplementary material, supported by a thoroughly commented IPython notebook that shows all analysis steps and may be modified by all users. Further reasons for the significantly lower values found in more recent studies remain a matter of speculation. On the one hand, the choice of tower position, e.g., central vs. edge spot within a homogeneous fetch, might have had a considerable effect on NH₃ concentration measurements. Studies like Flechard et al. (2011) report data from sites where the positions of determination were almost exclusively located in central position in order to represent the chosen land use as good as possible. In a number of former studies, however, research aims were more focused on local transport and dispersion away from point sources such as cattle urine patches, cattle sheds, and slurry tanks. Thus, higher values of NH₃ concentration formed the base for the derivation of deposition velocities. On the other hand, improvements in both measurement and modeling techniques could have also led to a lowered deposition regime. Optical devices such as absorption spectrometers (von Bobrutzki et al. 2010) use short and heated inlet tubes, thereby avoiding more efficiently wall surface reactions and memory effects. Consequently, more accurate input data generates better parameterizations for canopy resistances in surface-atmosphere exchange schemes.

Due to missing information in many studies, it was not possible to derive a robust dependency of deposition velocity on reference height. It is well known that concentration profiles are usually not strictly linear; therefore, a constant concentration gradient governing the deposition process is not always a valid assumption. However, a large number of authors did not report the respective reference height. If it was provided, in many cases, no details, e.g., on the consideration of zero plane displacement height were reported. The same holds true for reporting uncertainty estimates. Due to inconsistent use of terminology, omission of details on the uncertainty estimation techniques and on the nature of reported uncertainties (standard deviations, standard errors, confidence intervals, ranges), or simply no mention of uncertainty at all, it was not possible for us to do an error propagation and report more than ranges for the aggregated values of \( v_d \).

Note that we did not distinguish agricultural sites by different management practices. Some authors, e.g., Cui et al. (2011), explicitly report \( v_d \) during different phases of management and include fertilization periods in the annual average. In other cases, such as the data synthesis of Flechard et al. (2011), fertilization periods were excluded from dry deposition velocity estimates. Furthermore, many authors did not report whether average \( v_d \) values were obtained from long-term average concentrations and fluxes, or as an average of multiple individual (e.g., daily or hourly) \( v_d \) estimates, which may lead to differences in the significance of singular events, like emission periods shortly after fertilization, with regard to the average deposition velocity.

It is worth noting that more than half of the values for the ammonia deposition velocity are the results of inferential modeling or the use of chemical transport models and not of direct flux measurements, like those using aerodynamic gradient techniques, which may play a role regarding the fact that our \( v_d \) values are lower than those of comparable studies. However, recent technical improvements, both in the area of modeling (Flechard et al. 2013) and in measurement (von Bobrutzki et al. 2010), especially in the field of optical techniques such as open path DOAS (e.g., Volten et al. 2012) or QCL spectroscopy (e.g., Ferrara et al. 2012, based on the concept of Nelson et al. 2004), may lead to an increase of or at least to more reliable ammonia exchange studies in the near future.

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## Appendix

### Table 2  List of ammonia deposition velocities sorted by land use category

| Reference                        | Method | Specific | Mean       | Comment                                      | Weights |
|----------------------------------|--------|----------|------------|-----------------------------------------------|---------|
|                                  |        |          |            |                                               | $w_s$   |
|                                  |        |          |            |                                               | $w_c$   |
| **Coniferous forests**           |        |          |            |                                               |         |
| Builtjes et al. (2011)           | CTM    | 1.6      | 2.1        | Annual mean at $z_R=25$ m                      | 4       |
|                                  |        |          | 2.3        | Annual mean at $z_R=2.5$ m                      | 4       |
|                                  |        |          | 2.0        | Mean over all $z_R$                            |         |
| Kirchner et al. (2005)           | LIT    | 0.8–4.5  | 2.2        | Literature research ($n=1$)                     | 4       |
|                                  |        |          |            | Center of range                                |         |
| Mohr et al. (2005)               | INF    | 1.6      |            | Annual mean                                    | 4       |
| Staelens et al. (2012)           | LIT    | 2.9      |            | Literature research ($n=12$)                    | 4       |
| Zhang et al. (2009)              | INF    | 0.5      |            | Mean of two sites                              | 3       |
| Zimmermann et al. (2006)         | INF    | 3.3      |            | Annual mean                                    | 4       |
| **Deciduous forests**            |        |          |            |                                               |         |
| Builtjes et al. (2011)           | CTM    | 1.4      | 1.9        | Annual mean at $z_R=25$ m                      | 4       |
|                                  |        |          | 2.1        | Annual mean at $z_R=2.5$ m                      | 4       |
|                                  |        |          | 1.8        | Mean over all $z_R$                            |         |
| Fan et al. (2009)                | INF    | 0.3      |            | Annual mean                                    | 4       |
| Staelens et al. (2012)           | LIT    | 1.5      |            | Literature research ($n=4$)                     | 4       |
| Zhang et al. (2009)              | INF    | 0.3      |            | Mean of two sites                              | 2       |
| **Mixed forests**                |        |          |            |                                               |         |
| Endo et al. (2011)               | INF    | 0.5–0.9  | 0.7        | Range of ten sites                             | 4       |
|                                  |        |          |            | Center of range                                |         |
| Flechard et al. (2011)           | INF    | 1.7      |            | Mean of 29 sites                               | 4       |
| Neirynek et al. (2005)           | AGM    | 3.5      | 2.4        | Daytime                                        | 4       |
|                                  |        |          | 2.9        | Nighttime                                      | 4       |
|                                  |        |          | 1.5        | High NH₃ daytime                               | 4       |
|                                  |        |          | 3.7        | Low NH₃ daytime                                | 4       |
|                                  |        |          | 2.6        | Low NH₃ nighttime                              | 4       |
|                                  |        |          | 3.0        | Annual mean                                    |         |
| Neirynek and Ceulemans (2008)    | AGM    | 3.0      |            | Annual mean                                    | 4       |
| Neirynek et al. (2007)           | AGM    | 3.2      | 2.8        | Winter                                         | 4       |
|                                  |        |          | 3.4        | Summer                                         | 4       |
|                                  |        |          | 1.7        | Summer daytime                                 | 4       |
|                                  |        |          | 3.6        | Winter nighttime                               | 4       |
|                                  |        |          | 3.0        | Winter nighttime                               | 4       |
|                                  |        |          | 3.0        | Annual mean                                    |         |
| Zhang et al. (2009)              | INF    | 0.4      |            | Mean of three sites                            | 4       |

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| Reference                  | Method     | Specific | Mean | Comment                      | $w_s$ | $w_c$ |
|---------------------------|------------|----------|------|------------------------------|-------|-------|
| **Semi-natural sites**    |            |          |      |                              |       |       |
| Bajwa et al. (2008)       | CTM        | 1.0      |      | Summer, daytime              | 4     | 1     |
|                           |            | 0.1      |      | Summer, nighttime            |       |       |
|                           |            | 1.7      |      | Spring, daytime              |       |       |
|                           |            | 0.1      |      | Spring, nighttime            |       |       |
|                           |            | 0.8      |      | Fall, daytime                |       |       |
|                           |            | 0.1      |      | Fall, nighttime              |       |       |
|                           |            | 0.5      |      | Winter, daytime              |       |       |
|                           |            | 0.1      |      | Winter, nighttime            |       |       |
|                           |            |          |      | 0.6 Annual mean              | 4     | 4     |
| Benedict et al. (2013)    | INF        | 0.1–2.3  |      | Annual range                 | 4     | 4     |
|                           |            | 1.2      |      | Center of range              |       |       |
| Cape et al. (2008)        | CHA + INF  | 1.6      |      | Annual mean                  | 4     | 4     |
|                           |            | 0.3      |      | Annual mean, fumigated       |       |       |
| Endo et al. (2011)        | INF        | 0.2–0.6  |      | Range of ten sites           | 4     | 4     |
|                           |            | 0.4      |      | Center of range              |       |       |
| Flechard et al. (2011)    | INF        | 0.6      |      | Annual mean of 17 sites      | 4     | 4     |
| Hole et al. (2008)        | AGM        | 0.1      |      | Annual mean from measurements| 4     | 4     |
|                           | INF        | 0.3      |      | Model results for scenario “Grass”|     |       |
|                           |            | 0.6      |      | Model results for scenario “Tundra”|   |       |
| Horvath et al. (2005)     | AGM        | 1.1      |      | Vegetation period, daytime   | 4     | 4     |
|                           |            | 1.0      |      | Vegetation period, nighttime |       |       |
|                           |            | 1.1      |      | Vegetation period, whole day |       |       |
|                           |            | 0.7      |      | Dormant season, daytime      |       |       |
|                           |            | 0.9      |      | Dormant season, nighttime    |       |       |
|                           |            | 1.0      |      | Dormant season, whole day    |       |       |
|                           |            |          |      | 1.0 Annual mean              | 4     | 4     |
| Hurkuck et al. (in print) | AGM        | 0.7      |      | Annual mean                  | 4     | 4     |
| Jones et al. (2007)       | CHA        | 0.4–0.6  |      | Range during spring          | 1     | 1     |
|                           |            | 0.5      |      | Center of range              |       |       |
| Kirchner et al. (2005)    | LIT        | 0.5–2.2  |      | Literature research ($n=3$)  | 4     | 4     |
|                           |            | 1.4      |      | Center of range              |       |       |
| Milford et al. (2009)     | AGM        | 0.2      |      | Summer                       | 1     | 1     |
| Myles et al. (2011)       | LIT        | 1.8      |      | Literature research ($n=4$)  | 4     | 4     |
| Nemitz et al. (2004)      | AGM        | 0.6      |      | Daytime, dry                 | 1     | 2     |
|                           |            | 0.7      |      | Nighttime, dry               |       |       |
|                           |            | 1.8      |      | Daytime, wet                 |       |       |
|                           |            | 1.6      |      | Nighttime, wet               |       |       |
|                           |            | 1.2      |      | Spring mean                  |       |       |
| Phillips et al. (2004)    | AGM        | 3.9      |      | Summer, daytime              | 4     | 1     |
|                           |            | 0.8      |      | Summer, nighttime            |       |       |
|                           |            | 2.9      |      | Spring, daytime              |       |       |
|                           |            | 0.6      |      | Spring, nighttime            |       |       |
Table 2 (continued)

| Reference                  | Method | Specific | Mean | Comment                        | Weights | w_s (−) | w_c (−) |
|----------------------------|--------|----------|------|--------------------------------|---------|---------|---------|
|                            |        |          |      | 2.8 Fall, daytime              |         |         |         |
|                            |        |          |      | 0.1 Fall, nighttime            |         |         |         |
|                            |        |          |      | 2.4 Winter, daytime            |         |         |         |
|                            |        |          |      | 0.2 Winter, nighttime          |         |         |         |
| Staelens et al. (2012)     | LIT    | 1.4      |      | Literature research (n=13)    | 4       | 4       |         |
| Trebs et al. (2006)        | INF    | 1.0      |      | Fall                           | 1       | 2       |         |
| Water                      |        |          |      | 1.7 Annual mean                |         |         |         |
| Biswas et al. (2005)       | AGM    | 0.4      |      | Monsoon                        | 4       | 4       |         |
|                            |        |          |      | 0.6 Pre-monsoon                |         |         |         |
|                            |        |          |      | 0.5 Post-monsoon               |         |         |         |
|                            |        |          |      | 0.7 Annual mean at z_R=25 m    | 4       | 4       |         |
| Builtjes et al. (2011)     | CTM    | 0.7      |      | Annual mean at z_R=2.5 m       | 4       | 4       |         |
|                            |        |          |      | 1.0 Annual mean at z_R=1.0 m   | 4       | 4       |         |
|                            |        |          |      | 0.9 Mean over all z_R          | 4       | 4       |         |
| Smith et al. (2007)        | INF    | 0.6      |      | Summer                         | 1       | 2       |         |
| Urban sites                |        |          |      | 0.8 Annual mean                | 4       | 4       |         |
| Anatolaki and Tsitouridou  | SUS    | 0.8      |      | Annual mean                    | 4       | 4       |         |
| (2007)                     |        |          |      | 0.7 Annual mean at z_R=25 m    | 4       | 4       |         |
| Builtjes et al. (2011)     | CTM    | 0.7      |      | Annual mean at z_R=2.5 m       | 4       | 4       |         |
|                            |        |          |      | 0.9 Annual mean at z_R=1.0 m   | 4       | 4       |         |
|                            |        |          |      | 0.8 Mean over all z_R          | 4       | 4       |         |
| Hayashi and Yan (2010)     | LIT    | 0.5      |      | Annual mean from data synthesis| 4       | 4       |         |
| Poor et al. (2006)         | CTM    | 1.1      |      | Annual mean                    | 4       | 4       |         |
| Yang et al. (2010)         | INF    | 0.1      |      | Annual mean                    | 4       | 1       |         |
| Agricultural sites         |        |          |      | 0.3 Spring                      | 4       | 4       |         |
| Baek et al. (2006)         | AGM    | 6.3      |      | Summer                         | 1       | 1       |         |
| Builtjes et al. (2011)     | CTM    | 1.2      |      | Annual mean at z_R=25 m        | 4       | 4       |         |
|                            |        |          |      | 1.7 Annual mean at z_R=2.5 m   | 4       | 4       |         |
|                            |        |          |      | 1.9 Annual mean at z_R=1.0 m   | 4       | 4       |         |
|                            |        |          |      | 1.6 Mean over all z_R          | 4       | 4       |         |
| Cui et al. (2010)          | INF    | 0.3      |      | Spring                          | 4       | 4       |         |
|                            |        |          |      | 0.2 Summer                      | 4       | 4       |         |
|                            |        |          |      | 0.2 Fall                        | 4       | 4       |         |
|                            |        |          |      | 0.3 Winter                      | 4       | 4       |         |
|                            |        |          |      | 0.3 Annual mean                | 4       | 4       |         |
| Cui et al. (2011)          | INF    | 0.3      |      | Annual mean                    | 4       | 4       |         |
|                            | LIT    | 0.4      |      | Literature research (n=3)      | 4       | 4       |         |
| Delon et al. (2012)        | INF    | 0.3      |      | Annual mean of five sites      | 4       | 4       |         |
| Flechard et al. (2011)     | INF    | 0.2      |      | Annual mean of eight sites     | 4       | 4       |         |
| Hayashi et al. (2012)      | AGM    | 0.6      |      | Winter, fallow, daytime        | 2       | 1       |         |
|                            |        |          |      | 0.2 Winter, fallow, nighttime  | 2       | 1       |         |
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| Reference          | Method | Specific | Mean | Comment                  | $w_s$ | $w_c$ |
|--------------------|--------|----------|------|--------------------------|-------|-------|
| Katata et al. (2013) | INF    | 0.4–0.8  | 0.6  | Center of ranges         | 2     | 1     |
| Meyers et al. (2006)  | REA    |          | 4.7  | Summer                   | 1     | 1     |
| Myles et al. (2007)   | REA    | 1.3      |      | Daytime mean             | 1     | 1     |
| Myles et al. (2011)   | AGM    | 7.1      |      | Fall                     | 1     | 1     |
| Sommer et al. (2009)  | LIT    | 2.2      |      | Literature research ($n=4$) | 4     | 4     |
| Yang et al. (2010)    | INF    | 0.2      |      | Annual mean              | 4     | 4     |
| Zhang et al. (2009)   | INF    | 0.3      |      | Spring                   | 1     | 1     |
| Zhou et al. (2010)    | INF    | 0.3      |      | Spring                   | 4     | 4     |

Values listed under the column “Mean” were used in calculating weighted averages and medians, with the exception of duplicate values in Neirynck et al. (2007) and Neirynck and Ceulemans (2008).

*CTM* chemical transport model, *LIT* literature study, *INF* inferential modeling, *AGM* aerodynamic gradient technique, *BIO* biomonitoring, *SUS* surrogate surfaces, *CHA* chamber measurements.
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