# Chapter 21
# Variograms of Soil Properties for Agricultural and Environmental Applications

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*"Think left and think right and think low and think high. Oh, the things you can think up if only you try"!*

DR Suess

## 21.1 Geostatistics and Precision Agriculture

The previous chapter describes how precision agriculture can be used to improve farm management to achieve economic and environmental benefits. Short-range differences in soil attributes mean that spatially differentiated management can create economic or environmental benefits. Effective precision agriculture requires accurate soil mapping at subfield scales so that management practices can be modified. Improvements in farming technology, for instance, GPS-controlled farm equipment, decrease the difficulty and cost associated with spatially differentiated management. This improves the ease of implementation and makes high-resolution soil maps more valuable.

A key challenge for geostatistics in precision agriculture is the detection of soil variability at important subfield scales and the systematic incorporation of this variability into accurate field scale soil maps.

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## 21.2 Soil Survey, the Variogram and Kriging

Soil attributes are typically difficult and expensive to observe. As a result, soil attribute maps made for the purpose of precision agriculture are typically created from point observations which represent a small proportion of the area to be mapped. Estimates of soil attributes in unknown areas are based on the observations and an expectation of the regions between them. This process of predicting attributes in unobserved areas is known as kriging (explained in more detail in Chap. 10). Assumptions about spatial variability are typically derived from the variogram, which links spatial separation distance to expectations about variability. Chapters 10 and 11 explain the variogram, its uses and the different methods of calculating the variogram in more detail.

The variogram is sometimes called the ‘cornerstone of geostatistics’. Accurate estimation of the variogram is critical to the production of accurate soil maps. Because of the hidden nature of most soil attributes, we can usually only directly observe a small proportion of an area of interest. In Chap. 10, the distinction between the experimental or empirical variogram and the model variogram is described in some detail. The empirical variogram plots the average variance against separation distance for a number of distinct lags. The model variogram uses the information from the empirical variogram to estimate the expected variability at all lags. The purpose of the model variogram is to estimate the true underlying spatial variation at a level of detail that allows useful predictions.

Interpolation of results into unobserved points depends on the spatial structure estimated by the variogram. The closer the estimated variogram to the underlying spatial structure, the more accurate the subsequent interpolation. In general, a variogram computed from samples with finer spacing and more observations will estimate the underlying spatial structure more accurately than a variogram computed from samples with coarser spacing. Finer spacing allows the detection of spatial structure across more scales. The extent to which this is true will depend on the interaction of the spacing with the underlying spatial structure. For example, if there is no spatial relationship between points more than 5 m apart, then decreasing spacing from 50 m of separation distance to 10 m will not improve the variogram. We pause here to explain some key components of the variogram and how they are affected by survey design.

## 21.3 Key Components of the Variogram

While the variogram can take many forms (see Chap. 10, Sect. 10.1.1, for detail on some commonly used models), there are three components which are typically considered the most important indicators of spatial structure. Shown in the stylised diagram in Fig. 21.1 and subsequently described, these components are the nugget, the sill and the range. The estimation of each of these parameters depends strongly on the sampling design.

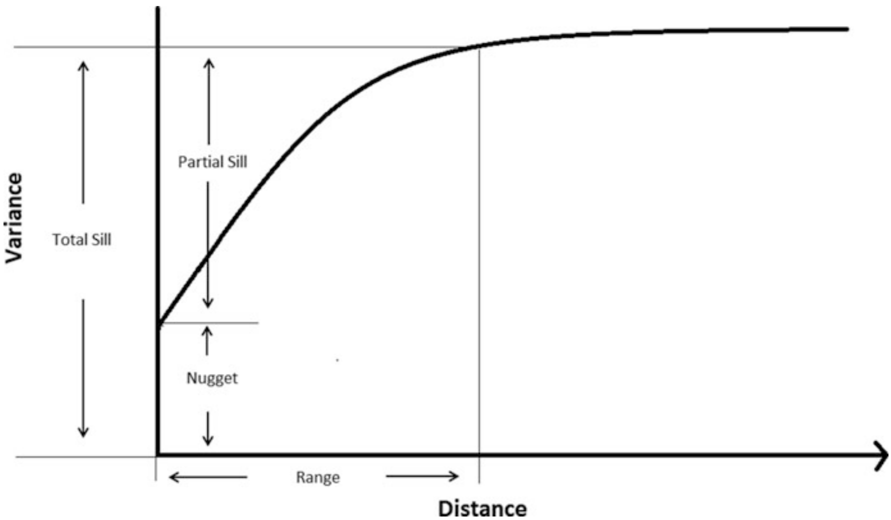


**Fig. 21.1** Stylised diagram, showing the three most important indicators of spatial structure, the nugget, the sill and the range

## *21.3.1 Nugget*

In principle the nugget effect captures nonspatial variation: measurement error; random variation. However, in practice the nugget will also capture spatial variation that occurs at scales less than the smallest sampling interval. If the sampling interval is wider than an important scale of spatial variation, then this will increase the nugget. Aliquotting (pooling of samples) will decrease the nugget. A larger support (area over which the sample is taken) will also decrease the nugget.

## *21.3.2 Total Sill*

The total sill is defined as the maximum variability that can be expected for a particular soil property. Beyond a certain separation distance (the range, see below), the expected variability will not increase past the value of the total sill (or in some cases will increase only very slowly and slightly past the sill). Only bounded variogram models have a sill. The total sill is more likely to be affected by the number of samples and the wider separation distance than the minimum sampling spacing. When modelling spatial variability at a field scale, it is unlikely that the maximum variability of the soil will be reached. However, unbounded models are rarely fit. In the context of precision agriculture, we can think of the total sill as being the maximum variability within this particular context or a local maximum. If we extended the sampling to a regional level, it is likely we would reach another magnitude of variability.

### 21.3.3 Partial Sill

The distance between the nugget and the sill is known as the partial sill. The partial sill is the component of variation that can be spatially attributed. In Fig. 21.1, the semivariance increases linearly with distance at short separation distances. As the separation distance increases, the rate of increase in the semivariance decreases, before eventually reaching a plateau as the semivariance reaches the total sill. This pattern is commonly found in variogram models (see Chap. 10 for more detail on the functional forms). Accurately determining the change in variability between the nugget and the sill requires sufficiently dense sampling at appropriate scales of variability.

### 21.3.4 Range

Like the lag and the sill, the range estimated by the theoretical variogram will be strongly affected by the sampling design. As the lag increases, the confidence intervals widen (Oliver and Webster 2014) which can make it difficult to accurately fit a variogram at lags approaching the full extent. Precision agriculture surveys are typically conducted over areas from a few hectares to a few hundred hectares. This precludes them from capturing landscape or continental scale variability. Despite this, the majority of variogram fits from precision agriculture studies are bounded. The modelled range and sill can be thought of as the ‘local sill’ associated with the ‘local range’ associated with the particular extent and spacing of that survey. It is very likely that if the extent of the survey was increased, another degree of variability would be found. It is critical to consider the potential effect of both the extent and the spacing on the range when considering precision agriculture studies and how their findings may inform your own work.

## 21.4 Soil Survey Design: Capturing Spatial Variability

The task of ensuring that a soil survey captures the necessary scales of variability is not a trivial one. The expense of a soil survey, and the commonly destructive nature of soil sampling, creates a pressure to reduce the number of sampling points as much as possible. However, if sampling is insufficient or too sparse (relative to the underlying spatial structure), it will compromise the variogram and thus the accuracy of the maps which are calculated from it. It is noted in Chap. 11 that one of the chief difficulties associated with the design of a soil survey for estimating a variogram is that the underlying spatial structure is unknown at the time the survey is designed. If the underlying spatial structure of a soil attribute is known, we can design a soil survey sufficiently to create a map at a particular level of detail.

Where budget allows it, the best practice is to undertake a preliminary soil survey to estimate important scales of variation before a more comprehensive soil survey is designed. This survey should be nested in its design to increase the chances of capturing important scales of variability (Pettitt and McBratney 1993; Webster and Oliver 2001). However, a preliminary survey will rarely be economically feasible. If it is not possible to conduct a preliminary survey, a soil survey design is likely to benefit from the consultation of alternative sources of information about soil variability, such as existing literature or covariates.

Budget or practical pressures may be sufficient to impede the collection of sufficient data to reliably calculate an empirical variogram. A stable variogram calculated from classical geostatistical methods (as described in Chap. 10) requires around 100 observations. More modern methods (as described in Chap. 11) typically require around 50. It is not possible to estimate spatial variability at distances less than the minimum separation distance. In cases where there are few or widely spread soil observations, alternative sources of information may be useful for the calculation of a variogram for kriging.

The expense of gathering soil observations creates a need for cheaper sources of information about soil variability, either to assist in the planning of a soil survey or to use in the process of kriging itself. Many authors have identified sources and strategies for the production of this information.

## 21.5 Variograms from the Precision Agriculture Literature

Variograms calculated for the same soil attribute may be a useful source of information. However, variograms calculated for the same property can vary significantly for a number of reasons that should be carefully considered. As outlined in Chap. 12, parent material, soil type, land use and climate will all have an effect on soil spatial variability. Consideration of these factors will be important in the selection of a variogram. Unfortunately, knowledge about soil spatial variability does not extend to the quantification of which of these factors are most important for determining spatial variability of different soil attributes.

The underlying variability of soil attributes might be different for the reasons mentioned above. In addition, the methods used to detect soil variability might create differences in the shape of the variogram. Different projects may focus on detecting variability at different scales for management or budget reasons. Even if the soil type is similar between two studies, the spatial variability might not be measured in a way that provides useful information.

It is also very important that the statistical methods used are assessed critically, before results are used or duplicated. There are a number of variograms included in Tables 21.1, 21.2, 21.3, 21.4, 21.5, 21.6, 21.7 and 21.8 which appear to use insufficient sample numbers for variogram estimation. There are several variograms which appear to assign spatial structure at a magnitude that appears to be meaningless relative to the units (i.e. total sill of less than 1% for the soil texture fraction).[1] These results have been included for completeness, but we wish to draw the readers' attention to the fact that some of the variograms included in this collection may have issues associated with them.

We describe below some key trends we have noted in the compilation of soil variograms and include a graphical summary of the variograms we have compiled. Variograms from McBratney and Pringle (1999) are included as well as those we have collected from the intervening period. Summary details and references for each variogram are given in Tables 21.1, 21.2, 21.3, 21.4, 21.5, 21.6, 21.7 and 21.8. We encourage the reader to consult each source directly for more detail about the sampling design and process.

**Variograms for the same soil attribute from existing literature can be a useful source of information about field scale soil. It is important to exercise caution when consulting this literature, as variograms have been created from different soil types, for different purposes and possibly with important methodological limitations.**

## *21.5.1 Field Scale Soil Variograms: Key Trends*

### 21.5.1.1 Variogram Forms

Across all soil properties, a number of functional forms were fit to variograms. For each soil property, at least one study found no spatial structure (i.e. pure nugget) to be the best fit. This suggests that either the spatial structure occurs at scales finer than those surveyed or that the variability in the property in question is less than the experimental error. Spherical and exponential variograms were commonly used. Some papers described the functional form as 'experimental'. These models were fit with an exponential model.

[1]In some cases the magnitude of the nugget and partial sill is extremely small compared to the magnitude of the standard deviation. This may suggest that the data has been transformed in some way before the variogram has been fit. We have reported the results as in the original article. These results should be interpreted with particular caution.

**Table 21.1** Compilation of key properties for clay variograms

| | Reference | Location | Climate | Soil type | Land use | Timing | Measurement method | Study area (ha) | Sample size | Mean | Standard deviation | Depth (cm) | Model | Nugget | Partial sill | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| a | Lopez-Granados et al. (2002) (site two) | Caracol, Southern Spain | | Vertic Xerochep | Crop | Before sowing | Bouyoucos densimeter | 6 | 84 | 26.3 | 12 | 0–0.10 | Exponential | 61 | 84 | 29.9 |
| b | Adderley et al. Adderley et al. (1997) | Nigeria | | | Trees | | | 30 | 480 | 25.8 | 9.1 | 0–0.10 | Experimental | 30 | 110 | 250 |
| c | Lopez-Granados et al. (2002) (site one) | Monclova, Southern Spain | | Alfisol | Crop | Before sowing | Bouyoucos densimeter | 11.2 | 80 | 19.6 | 10.8 | 0–0.10 | Nugget | 113 | 0 | 0 |
| d | Oliver and Webster (1987), (10–15) | Wyre Forest, England | | Acid brown loam | Forest | | | 0.025 | 100 | | | 0–0.15 | Exponential | 24.9 | 50.7 | 51.6 |
| e | Oliver and Webster (1987), (0–5) | Wyre Forest, England | | Acid brown loam | Forest | | | 0.025 | 100 | 24.4 | 10.8 | 0–5 | Exponential | 14.34 | 51.8 | 65.7 |
| f | Kerry and Oliver (2007) | | | | | | | 15 | 118 | 47.5 | 6.2 | | Spherical | 0.72 | 36.72 | 71.48 |
| g | Nolin et al. (1996) | Quebec | | Aquepts | Crop | | | 10 | 130 | 44.3 | 6 | 0–15 | Spherical | 10.8 | 20.9 | 76 |
| h | Shatar (1996) | Moree, Australia | | Vertisol | Crop | | | 15 | 114 | 49 | 5.5 | 15–30 | Spherical | 17 | 13.5 | 310 |
| i | Kerry and Oliver (2007) | | | | | | | 44 | 294 | 17.9 | 7.3 | | Spherical | 4.19 | 22.9 | 152 |
| j | Farooque et al. (2012) (site two) | Nova Scotia, Canada | | Sandy loam, orthic humo-ferric podzols | Orchard | | Bouyoucos densimeter | 1.6 | 86 | 9.6 | 4 | 0–15 | Spherical | 8.08 | 17.91 | 65.5 |
| k | Miller et al. (1988) | Sacramento, California | | Xererts, Xerochrepts | Crop | | | 8 | 99 | 37.1 | 4.6 | Surface | Spherical | 7 | 14 | 75 |
| l | Shouse et al. (1990) | Texas, USA | | Vertisol | | | | 0.3 | 203 | 40 | 3.9 | 0–30 | Exponential | 11.7 | 4.8 | 8.47 |

(continued)

**Table 21.1** (continued)

| | Reference | Location | Climate | Soil type | Land use | Timing | Measurement method | Study area (ha) | Sample size | Mean | Standard deviation | Depth (cm) | Model | Nugget | Partial sill | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| m | Kerry and Oliver (2007) | United Kingdom | | | | | | 10.5 | 205 | 30.2 | 5.8 | 0–15 | Spherical | 3.12 | 11.99 | 99.86 |
| n | Liu et al. (2008) | Henan Province, Central China | Monsoon climate 14.6C, 680 mm | Clay loam to loam | Tobacco plantation | Before sowing | Bouyoucos densimeter | 87 | 81 | 41.7 | 3.4 | | Spherical | 2.72 | 11.78 | 609 |
| o | Williams (1987) (four directions average) | Oklahoma | | Paleustolls | Crop | | | 1.62 | 108 | 22 | 2.3 | 0–30 | Experimental | 8.38 | 4.88 | 52.5 |
| p | Shouse et al. (1990), (field 1) | Texas, USA | | Vertisol | | | | 0.3 | 182 | 51 | 3.1 | 0–30 | Exponential | 3.8 | 6.4 | 11.89 |
| q | Shukla et al. (2004) | Gross-Enzersdorf, Austria | 510 mm, 10C | Loam to sandy loam | Crop | May | Pipette method | 6.25 | 60 | 46.8 | 4.6 | 0–15 | Spherical | 5.24 | 4.27 | 347 |
| r | Shouse et al. (1990) | Texas, USA | | Vertisol | | | | 0.3 | 205 | 46.1 | 2.6 | 0–30 | Spherical | 3.5 | 3.1 | 36.58 |
| s | Panagopoulos and Antunes (2008) | Algarve region, south Portugal | | | | | | 400 | 81 | 32.7 | 7 | 0–20 | Gaussian | 4.83 | 5.77 | 1,997.8 |
| t | Kristensen et al. (1995) Riso | Riso, Denmark | | Sandy loam/sandy clay loam | Crop | | | 10.9 | 270 | | | 0–25 | Exponential | 0 | 6 | 37 |
| u | Kristensen et al. (1995) (Vindum) | Vindum, Denmark | | Sandy loam | Crop | | | 10 | 302 | | | 0–25 | Exponential | 0 | 4.8 | 450 |
| v | Kilic et al. (2012), (5 years of cultivation) | Kaz Lake of Tokat, Turkey | 436 mm, 12C | Typic ustifluvent Clay loam to sandy clay loam | Crop/horticulture | | Bouyoucos hydrometer | 0.8 | 46 | 21.7 | 6.3 | | Spherical | 0.65 | 1.41 | 310.9 |
| w | Tabor et al. (1985) | Arizona | | Haplargid/mollisol | Crop | | | 13 | 49 | 32.1 | 5.8 | 0–20 | Linear | 1.68 | 60.32 | 500 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| x | Kilic et al. (2012) | Kaz Lake of Tokat, Turkey | 436 mm, 12C | Typic ustifluvent Clay loam to sandy clay loam | Marshy plants | | Bouyoucos hydrometer | 0.8 | 46 | 29.8 | 7.4 | 0–20 | Spherical | 0.69 | 0.81 | 207.8 |
| y | Ayoubi et al. (2007) | Golestan Province, Iran | | Fine, mixed, thermic, fluventic haploxerepts | Crop | Before plant-ing | Hydrometer method (day, 1965); | 1.8 | 101 | 56.3 | 1.1 | | Spherical | 0.67 | 0.66 | 25.83 |
| z | Kilic et al. (2012) cultivation | Kaz Lake of Tokat, Turkey | 436 mm, 12C | Typic ustifluvent Clay loam to sandy clay loam | Crop/ horticul-ture | | Bouyoucos hydrometer | 0.8 | 46 | 20.4 | 5.2 | | Linear | 0.99 | 0 | 85.66 |
| aa | De Souza (2010)-site two | Araras, Southeast Brazil | Wet summer, dry winter | Oxisol (typic haplustox) | Cropping | Fall of 2004 | | 22 | 90 | 34 | 0.2 | 0–20 | Spherical | 0 | 0.68 | 340 |
| ab | de Souza et al. (2010) – site one | Araras, Southeast Brazil | Wet summer, dry winter | Oxisol (typic haplustox) | Cropping | Fall of 2003 | | 20 | 80 | 26.1 | 0.5 | 0–20 | Spherical | 0.04 | 0.42 | 393 |
| ac | Kerry and Oliver (2007) | | | | | | | 6.9 | 109 | 4.1 | 1 | | Spherical | 0.06 | 0.39 | 96.17 |
| ad | Molin et al. (2013)- field one | Sao Palo, Southeast Brazil | | Typic dystrudoxes | | | | 19 | 42 | 21.5 | 5.1 | 0–20 | Spherical | 0 | 0.15 | 153 |
| ae | Molin et al. (2013) – field two | Sao Palo, Southeast Brazil | | Typic hapludoxes | | | | 22 | 92 | 23.1 | 3.7 | 0–20 | Spherical | 0.01 | 0.02 | 307.3 |
| af | Farooque et al. (2012): site one | Central Nova Scotia, Canada | Sandy loam, ferric podzols | | | | | 1 | 56 | 41.9 | 4.4 | 0–15 | Linear | 0.01 | 19.16 | 23.7 |

[a]Unless otherwise specified mm refers to annual average rainfall, and C refers to average annual temperature

**Table 21.2** Compilation of key properties for sand variograms

| | Reference | Location | Climate | Soil type | Land use | Timing | Measurement method | Study area (ha) | Sample size | Mean | Standard devia-tion | Depth (cm) | Model | Nugget | Partial sill | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| a | Adderly et al. (1997) | Nigeria | | | Trees | | | 30 | 157 | 56.8 | 10 | 0–10 | Experimental | 10 | 190 | 250 |
| b | Lopez-Granados et al. (2002) site two | Caracol, Southern Spain | | Vertic Xerochep | Crop | | Bouyoucos densimeter | 6 | 84 | 33.4 | 13.4 | 0–10 | Spherical | 85 | 99 | 84.8 |
| c | Farooque et al. (2012) – site two | Central Nova Scotia, Canada | | Sandy loam, orthic humo-ferric podzols | Orchard | | | 1.6 | 86 | 48.7 | 12.5 | 0–15 | Spherical | 68.8 | 106.4 | 67.9 |
| d | Lopez-Granados et al. (2002) site one | Monclova, Southern Spain | | Alfisol | Crop | | Bouyoucos densimeter | 11.2 | 80 | 57.4 | 8.5 | 0–10 | Nugget | 69 | 0 | 0 |
| e | Liu et al. (2008) | Henan Province, Central China | Monsoon 14.6C, 680 mm | Clay loam to loam, | Tobacco plantation | Before sowing | Bouyoucos densimeter | 87 | 81 | 43.8 | 4.8 | 0–20 | Spherical | 7.7 | 32.43 | 657 |
| f | Shatar (1996) | Moree, Australia | | Vertisol | Crop | | | 15 | 114 | | | 15–30 | Spherical | 20 | 17 | 300 |
| g | Miller et al. (1988) | Sacramento, California | | Xererts, Xerochrepts | Crop | | | 8 | 99 | 20.2 | 5.9 | Surface | Spherical | 0.6 | 33.4 | 75 |
| h | Farooque et al. (2012): site one | Central Nova Scotia, Canada | | Sandy loam, orthic humo-ferric podzols | Orchard | | | 1 | 56 | 49.5 | 4.5 | 0–15 | Linear | 18.75 | 18.75 | 85.86 |
| i | Wiliams et al. (1987), four directions averaged | Oklahoma, USA | | Paleustolls | Crop | | | 1.62 | 108 | 27 | 4.8 | 0–30 | Experimental | 8 | 9.25 | 62.5 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| j | Tabor et al. (1985) | Arizona, USA | | Haplargid/mollisol | Crop | | | 13 | 49 | 41.7 | 8.4 | 0–20 | Linear | 15.4 | 101.4 | 300 |
| k | Shouse et al. (1990) | Texas, USA | | Vertisol | | | | 0.3 | 205 | 21.1 | 3.3 | 0–30 | Spherical | 6.2 | 5.2 | 22.86 |
| l | Campbell (1977) Pawnee | Kansas, USA | | | | | | 1.6 | 160 | 8.5 | 2.9 | | Experimental | 2.2 | 0.8 | 40 |
| m | Kilic et al. (2012) | Kaz Lake of Tokat, Turkey | 436 mm, 12C | Typic ustifluvent clay loam to sandy clay loam | Crop/ hor-ticulture | | Bouyoucos hydrometer | 0.8 | 46 | 25.5 | 9.7 | 0–20 | Exponential | 0.75 | 1.13 | 200.4 |
| n | Kilic et al. (2012) – 5 years of cultivation | Kaz Lake of Tokat, Turkey | 436 mm, 12C | Typic ustifluvent Clay loam to sandy clay loam | Crop/ hor-ticulture | | Bouyoucos hydrometer | 0.8 | 46 | 33.5 | 10.3 | | Exponential | 0.87 | 0.87 | 306 |
| o | Kilic et al. (2012) – cultivation | Kaz Lake of Tokat, Turkey | 436 mm, 12C | Typic ustifluvent Clay loam to sandy clay loam | Crop/ hor-ticulture | | Bouyoucos hydrometer | 0.8 | 46 | 50.8 | 7.9 | | Linear | 1.02 | 0 | 85.66 |
| p | Campbell (1977) Ladysmith | Kansas, USA | | | | | | 1.6 | 160 | 1.2 | 0.3 | | Experimental | 0.04 | 0.04 | 30 |
| q | Ayoubi et al. (2007) | Golestan Province, Iran | | Fine, mixed, thermic, fluventic haploxerepts | Crop | Before plant-ing | Hydrometer method | 1.8 | 101 | 2.2 | 0.1 | 0–30 | Gaussian | 0.01 | 0 | 91.41 |

**Table 21.3** Compilation of key properties for pH variograms

| | Reference | Location | Climate | Soil type | Land use | Timing | Measurement method | Study area (ha) | Sample size | Mean | Standard deviation | Depth (cm) | Model | Nugget | Partial sill | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| a | Kilic et al. (2012) (unmodified) | Kaz Lake of Tokat, Turkey | 436 mm, 12C | Typic ustifluvent | Crop | | Water 1:2.5 | 0.8 | 46 | 7.9 | 0.1 | 0–20 | Exponential | 0.8 | 0.82 | 209.6 |
| b | Sidorova et al. (2012) | Northwestern Russia | | | Crop | Before sowing | KCl | | 72 | 5.6 | 0.2 | 23 | Spherical | 0.08 | 1 | 93.1 |
| c | Kilic et al. (2012) (20 year) | Kaz Lake of Tokat, Turkey | 436 mm, 12C | Typic ustifluvent. | Crop | | Water 1:2.5 | 0.8 | 46 | 8.1 | 0.2 | 0–20 | Linear | 1.03 | 0 | 85.66 |
| d | Kilic et al. (2012) (5 year) | Kaz Lake of Tokat, Turkey | 436 mm, 12C | Typic ustifluvent | Crop | | Water 1:2.5 | 0.8 | 46 | 7.8 | 0.2 | 0–20 | Linear | 1.01 | 0 | 85.66 |
| e | Thompson et al. (2004) – site one | Alabama, USA | | | Crop | | | 0.4 | 71 | | | 11* | Spherical | 0.05 | 0.71 | 186.2 |
| f | Pierce et al. (1995) (Durand) | Durand, USA | | Alfisol, fine loam | Crop | | | 16 | 165 | 6.6 | 0.9 | 0–5 | Spherical | 0.13 | 0.47 | 354 |
| g | Machado et al. (2007) | Uberlandia, Brazil | Tropical humid with dry season | Red latosol, moderate clayey texture | Crop | | Water: 1:1 | 25 | 121 | 6 | 0.4 | 0–20 | Spherical | 0.07 | 0.51 | 150 |
| h | Thompson et al. (2004) (site three) | Alabama, USA | | | Crop | | | 0.4 | 48 | | | 11 | Spherical | 0.11 | 0.43 | 168.9 |
| i | Mulla (1993) | Washington, USA | | Ultic haploxeroll | Crop | | | 8 | 172 | 6.1 | 0.7 | 0–30 | Spherical | 0.17 | 0.26 | 132 |
| j | Pierce et al. (1995) (Adrian) | Adrian, USA | | Alfisol, loam | Crop | | | 10 | 74 | 6.5 | 0.9 | 0–5 | Spherical | 0.08 | 0.32 | 95 |
| k | Camacho-Tamayo et al. (2007) (site one) | Puerto Lopez, Colombia | 2,375 mm 27C | Typic haplustox | Crop | May 04 | Water (1:1) potentiometer | 1.875 | 42 | 5.1 | 0.4 | 0–10 | Exponential | 0.09 | 0.31 | 410 |
| l | Webster and McBratney (1987) | Suffolk, England | | | Crop | | Water | 77 | 436 | 7.7 | 0.6 | | Spherical | 0.02 | 0.33 | 185 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| m | Uehara et al. (1985) | Sitiung, Indonesia | | | Crop | | | 0.0784 | 137 | | | | Experimental | 0 | 0.35 | 4 |
| n | de Souza et al. (2010) (site one) | Araras, Southeast Brazil | Wet summer, dry winter | Oxisol (typic haplustox) | Crop | Fall of 2003 | | 20 | 80 | 5.6 | 4 | 0–20 | Exponential | 0.07 | 0.23 | 148 |
| o | Adderley et al. (1997) | Nigeria | | | Forestry | | | 30 | 480 | 6.3 | 0.5 | 0–10 | Exponential | 0.15 | 0.1 | 250 |
| p | de Souza et al. (2010) (site two) | Araras, Southeast Brazil | Wet summer, dry winter | Oxisol (typic haplustox) | Crop | Fall of 2004 | | 22 | 90 | 5.7 | 0.5 | 0–20 | Spherical | 0.01 | 0.23 | 97 |
| q | Pierce et al. (1995) (Plainwell) | Plainwell, USA | | Entisol, loamy sand | Crop | | | 22 | 174 | 6.7 | 0.4 | 0–20 | Spherical | 0.06 | 0.15 | 190 |
| r | Thompson et al. (2004) (site two A) | Alabama, USA | | | Crop | | | 0.2 | 124 | | | 22 | Spherical | 0.09 | 0.1 | 393.2 |
| s | Birrell et al. (1996) | Missouri, USA | | | | | | 28 | 504 | | | 0–15 | Spherical | 0.06 | 0.11 | 125 |
| t | Thompson et al. (2004) (site two B) | Alabama, USA | | | Crop | | | 0.4 | 58 | | | 22 | Spherical | 0.05 | 0.05 | 181.1 |
| u | Kristensen et al. (1995) (Riso) | Riso, Denmark | | Sandy loam/sandy clay loam | Crop | | | 10.9 | 270 | | | 0–25 | Exponential | 0 | 0.1 | 17 |
| v | Kristensen et al. (1995) (Vindum) | Vindum, Denmark | | Sandy loam | Crop | | | 10 | 302 | | | 0–25 | Exponential | 0 | 0.09 | 19 |
| w | Liu et al. (2008) | Henan Province, Central China | Monsoonal 14.6C, 680 mm | Clay loam to loam, | Crop | Before sowing | Water (1: 2.5) | 87 | 81 | 7.7 | 0.3 | 0–20 | Spherical | 0.01 | 0.06 | 308 |
| x | Mondo et al. (2012) | Sao Paulo, Brazil | Not specified | | Crop | After | | 22 | 33 | 5 | 0.2 | 0–20 | Gaussian | 0.02 | 0.05 | 650 |

(continued)

**Table 21.3** (continued)

| | Reference | Location | Climate | Soil type | Land use | Timing | Measurement method | Study area (ha) | Sample size | Mean | Standard deviation | Depth (cm) | Model | Nugget | Partial sill | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| y | Laslett et al. (1987) | Brisbane, Australia | | | Pasture | | CaCl2 | 1 | 121 | 4.5 | 0.2 | | Spherical | 0.02 | 0.03 | 55 |
| z | Campbell (1977) (Pawnee) | Pawnee. Kansas, USA | | | | | CaCl2 (1:2) | 1.6 | 160 | 6.5 | 0.3 | | Experimental | 0.04 | 0 | 0 |
| aa | Silva et al. (2003) | Santa Maria, Brazil | | Ultisol dystrophic hapludalf | Crop | Before sowing | Water 1:1 | 0.3 | 192 | 4.9 | 0.1 | 0–20 | Spherical | 0 | 0.02 | 18.66 |
| ab | Campbell (1977) (Ladysmith) | Ladysmith, Kansas, USA | | | | | CaCl2 (1:2) | 1.6 | 160 | 6.5 | 0.2 | | Experimental | 0.02 | 0 | 0 |
| ac | Shatar (1996) | Moree, Australia | | Vertisol | Crop | | CaCl2 (1:5) | 15 | 114 | 7.4 | 0.2 | 5:30 | Spherical | 0.01 | 0.01 | 310 |
| ad | Tabor et al. (1985) | Arizona | | Haplargid/Mollisol | Crop | | | 13 | 49 | 7.3 | 0.2 | 0–20 | Linear | 0.02 | 0.06 | 500 |
| ae | Lopez-Granados et al. (2002) (site one) | Monclova, Southern Spain | | Alfisol | Crop | Before sowing | 0.1 mol KCl | 11.2 | 80 | 7.8 | 0.1 | 0–100 | Spherical | 0 | 0.01 | 66 |
| af | Lopez-Granados et al. (2002) (site two) | Caracol, Southern Spain | | Vertic Xerochep | Crop | Before | 0.1 mol KCl | 6 | 84 | 7.7 | 0.1 | 0–100 | Nugget | 0.01 | 0 | 0 |
| ag | Shukla et al. (2004) | Gross-Enzersdorf, Austria | 510 mm 10C | Loam to sandy loam | Crop | May | | 6.25 | 60 | NA | NA | 0–15 | Spherical | 0.01 | 0 | 158 |
| ah | Ayoubi et al. (2007) | Golestan Province, Iran | | Fluventic haploxerepts | Crop | Before sowing | 0.1 mol KCl | 1.8 | 101 | 7.9 | 0 | 0–30 | Spherical | 0.001 | 0.001 | 24.39 |

*Assuming 11 cm were taken from topsoil.

**Table 21.4** Compilation of key properties for carbon variograms

| | Reference | Location | Climate | Soil type | Land use | Timing | Measurement method | Study area (ha) | Sample size | Mean | Standard deviation | Depth (cm) | Model | Nugget | Partial sill | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| a | Farooque et al. (2012) (site one −1) | Central Nova Scotia, Canada | | Sandy loam, podzols | Orchard | May July 2009 | Om (LOI) | 1 | 56 | 6.6 | 1.5 | 0–15 | Sph. | 1.14 | | |
| b | Farooque et al. (2012) (site one −2) | Central Nova Scotia, Canada | | Sandy loam, podzols | Orchard | Jun 10 | Om (LOI) | 1 | 56 | 6.6 | 1.4 | 0–15 | Sph. | 1.11 | 2.28 | 76.1 |
| c | Panagopoulos and Antunes (2008) | Algarve region of south Portugal | Mediterranean | Mostly lithosols | Forestry, crop | | OM (WB-wet) | 400 | 81 | 1.2 | 0.5 | 0–20 | Exp. | 1.63 | 2.14 | 70.23 |
| d | Farooque et al. (2012) (site two −2) | Central Nova Scotia, Canada | | Sandy loam, podzols | Orchard | Jun 11 | Om (LOI) | 1 | 56 | 24 | 5.7 | 0–16 | | 0.25 | 1.95 | 1997.8 |
| e | Farooque et al. (2012) (site two −1) | Central Nova Scotia, Canada | | Sandy loam, podzols | Orchard | May July 2009 | Om (LOI) | 1.6 | 86 | 4.9 | 1.3 | 0–15 | Exp. | 0.22 | 1.86 | 13.7 |
| f | Kilic et al. (2012) (5 years) | Kaz Lake of Tokat, Turkey | 436 mm, 12C | Typic ustifluvent | Crop | | OM (WB-wet) | 0.8 | 46 | 1 | 0.3 | 0–20 | Exp. | 0.09 | 1.82 | 14.6 |
| g | Nolin et al. (1996) | Quebec, Canada | | Aquepts | Crop | | OC | 10 | 130 | 2.8 | 0.7 | 0–15 | Sph. | 0.08 | 1.23 | 224.5 |
| h | Kristensen et al. (1995), (Riso) | Riso, Denmark | | Sandy loam-sandy clay loam | Crop | | OC | 10.9 | 270 | | | 0–25 | Exp. | 0 | 0.61 | 343 |
| i | Kilic et al. (2012) (10 years) | Kaz Lake of Tokat, Turkey | 436 mm, 12C | Typic ustifluvent | Crop | | OM (WB-wet) | 0.8 | 46 | 0.7 | 0.3 | 0–20 | Exp. | 0 | 0.43 | 99 |
| j | Kilic et al. (2012) (uncultivated) | Kaz Lake of Tokat, Turkey | 436 mm, 12C | Typic ustifluvent | Crop | | OM (WB-wet) | 0.8 | 46 | 1.6 | 0.4 | 0–20 | Lin. | 0.33 | 0.35 | 9.6 |
| k | Mulla (1993) | St. John, Washington, USA | | Ultic haploxeroll | Crop | | OC | 8 | 172 | 1.2 | 0.5 | 0–30 | Sph. | 0.05 | 0 | 85.66 |

(continued)

**Table 21.4** (continued)

| | Reference | Location | Climate | Soil type | Land use | Timing | Measurement method | Study area (ha) | Sample size | Mean | Standard deviation | Depth (cm) | Model | Nugget | Partial sill | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| l | Gutierrez et al. (2010) | Municipality of Pasca, Colombia | 1,800 mm, 16¬C | Entisols and others | Horticulture | | OC | 1.5 | 64 | 6.4 | 0.3 | 0–20 | Sph. | 0.17 | 0.19 | 114 |
| m | Nanni et al. (2011) | Sao Paulo state, Brazil | Meso-thermic climate | Oxisols, entisols, alfisols, ultisols, inceptisols and mollisols | Crop | | OM[b] | 184 | 184 | 0.7 | 0.4 | 0–20 | Sph. | 0.05 | 0.24 | 10,240 |
| n | Zanão Júnior et al. (2010) | South-eastern Brazil | 1,500 mm | Oxisol hapludox (medium clay) | Crop | May to June 2003 | OM | 25 | 121 | 1.7 | 0.2 | 0–10 | Gaus | 0.05 | 0.15 | 691 |
| o | Cahn et al. (1994) 0.25 ha | Central Illinois | | Mollisol | Crop | | OC | 0.25 | 200 | 1.7 | 0.3 | 0–15 | Exp. | 0 | 0.15 | 539 |
| p | Kristensen et al. (1995), (Vindum) | Vindum, Denmark | | Sandy loam | Crop | | OC | 10 | 302 | | | 0–25 | Exp. | 0 | 0.18 | 50 |
| q | Shukla et al. (2004) | Gross-Enzersdorf, Austria | Temperate and continental, 510 mm 10C | Loam to sandy loam | Crop | May | OC | 6.25 | 60 | 1.4 | 0.2 | 0–15 | Sph. | 0.04 | 0.12 | 45 |
| r | Rowlands 1998; cited in McBratney & Pringle (1999)[c] | Wyalkatchem, WA | | Duplex | Crop | | OC | 75 | 56 | 0.7 | 0.2 | 0–10 | Sph. | 0.03 | 0.03 | 163 |
| s | de Souza et al. (2010) (site two) | Araras, Southeast Brazil | Wet summer, dry winter | Oxisol (typic haplustox) | Crop | Fall of 2004 | OM | 22 | 90 | 15.1 | 9.7 | 0–20 | Sph. | 0.02 | 0.03 | 638.985 |
| t | Mondo et al. (2012) | Sao Paolo, Brazil | | | Crop | After harvest | OM | 22 | 33 | 0.7 | 0.2 | 0–20 | Gaus | 0.01 | 0.04 | 304 |
| u | Camacho-Tamayo et al. (2008) (site 1) | Puerto Lopez, Colombia | 2,375 mm: 27C | Typic haplustox | Crop | May 04 | OC (mod-WB) | 1.9 | 42 | 1.3 | 0.2 | 0–10 | Exp. | 0 | 0.05 | 498.2 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| v | Shukla et al. (2004) | Gross-Enzersdorf, Austria | Temperate and continental, 510 mm 10C | Loam to sandy loam | Crop | May | OC | 6.25 | 60 | 1 | 0.2 | 0–15 | Sph. | 0.02 | 0.04 | 22.1 |
| w | Shatar (1996) | Moree, Australia | | Vertisol | Crop | | OC | 15 | 114 | 1.1 | 0.2 | 15–30 | Sph. | 0.01 | 0.02 | 184 |
| x | Zhang et al. 2016 | Jiangsu Province, China | | | Crop | 2012 | OM | 7 | 136 | | | | Sph. | 0 | 0.03 | 280 |
| y | de Souza et al. 2010 (site one) | Araras, Southeast Brazil | Wet summer, dry winter | Oxisol (typic haplustox) | Crop | Fall of 2003 | OM | 20 | 80 | 10.7 | 1.4 | 0–20 | Sph. | 0.01 | 0.04 | 38.6 |
| z | Amirinejad et al. 2011 | Uttar Pradesh, India | | Inceptisol | Crop | | OC (WB) | 19.6 | 145 | | | 0–15 | Gaus | 0.01 | 0.02 | 324 |
| aa | Kumhalova et al. 2011 (sampled 2005) | Prague, Ruzyne, Czech Republic | 526 mm: 7.9C | Haplic luvisol. | Crop | | OC | 11.5 | 70 | 2.1 | 0.2 | | Sph. | 0.02 | 0.02 | 380.73 |
| ab | Camacho -Tamayo et al. 2008 (site two) | Puerto Lopez, Colombia | 2,375 mm, 27 C | Typic hapludox | Crop | Aug 04 | OC (mod-WB) | 1.875 | 42 | 1.6 | 0.1 | 0–10 | Sph. | 0 | 0.01 | 240.5 |
| ac | Liu et al. 2010 | Henan Province, Central China | Monsoon climate 14.6C, 680 mm | Sandy to medium clay loam | Crop | After harvest, | OM (WB-wet) | 4 | 111 | 1 | 0.1 | 0–20 | Sph. | 0.01 | 0.02 | 33.5 |
| ad | Liu et al. 2008 | Henan Province, Central China | Monsoon climate 14.6C, 680 mm | Clay loam to loam | Crop | Before sowing | OM[d] | 87 | 81 | 0.7 | 0.1 | 0–20 | Sph. | 0.01 | 0.01 | 56.5 |
| ae | Ayoubi et al. 2007 | Golestan Province, Iran | | Fluventic haploxerepts | Crop | Before planting | Om (WB) | 1.8 | 101 | 1.5 | 0.1 | 0–30 | Sph. | 0.01 | 0.01 | 556 |
| af | Silva et al. 2003 | Santa Maria, Brazil | | Ultisol dystrophic hapludalf | Crop | Before sowing | OM [e] | 0.3 | 195 | 1.6 | 0.1 | 0–20 | Gaus | 0.01 | 0.01 | 29.28 |

(continued)

**Table 21.4** (continued)

| | Reference | Location | Climate | Soil type | Land use | Timing | Measurement method | Study area (ha) | Sample size | Mean | Standard deviation | Depth (cm) | Model | Nugget | Partial sill | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ag | Kumhalova et al. 2011 (sampled 2004) | Prague, Ruzyne, Czech Republic | 526 mm: 7.9C | Haplic luvisol | Crop | | OC | 11.5 | 70 | 1.7 | 0.2 | | Sph. | 0.01 | 0.01 | 9.5 |
| ah | Kumhalova et al. 2011 (sampled 2006) | Prague, Ruzyne, Czech Republic | 526 mm: 7.9C | Haplic Luvisol | Crop | | OC | 11.5 | 70 | 1.9 | 0.2 | | Sph. | 0.01 | 0.01 | 274.6 |
| ai | Goovaerts and Chiang 1993 (average) | Belgium | | Typic hapludalf | | | OC | 0.16 | 73 | 0.7 | 0.1 | 0–20 | Sph. | 0.01 | 0.05 | 244.7 |
| aj | Chung et al. 2008 | Korea | 12.7C, 1,560[a] | Coarse, loamy, mixed, non-acid, mesic | Crop | After harvest | OM[f] | 0.3 | 246 | 1.3 | 0.1 | 0–15 | Lin. | 0.01 | 0 | 11.5 |
| ak | Lopez-Granados et al. (2002) site one | Monclova, Southern Spain | | Alfisol | Crop | Pre planting | OM[g] | 11.2 | 80 | 0.9 | 0.1 | 0–10 | Nug. | 0.01 | 0 | NA |
| al | Lopez-Granados et al. (2002) site two | Caracol, Southern Spain | | Vertic Xerochep | Crop | Pre planting | OM[g] | 6 | 84 | 0.8 | 0.1 | 0–10 | Sph. | 0 | 0 | 0 |
| am | Chatterjee et al. 2015 | West Bengal, India | 1,443 mm, hot and humid | | Crop | After harvest | OC (WB) | 81 | 100 | 0.5 | 0.1 | 0–15 | Lin. | 0 | 0.01 | 44.8 |
| an | Kumhalova et al. 2011-(sampled 2007) | Prague, Ruzyne, Czech Republic | 526 mm: 7.9C | Haplic luvisol | Crop | Not specified | OC | 11.5 | 70 | 2 | 0.2 | | Sph. | 0 | 0.01 | 58 |
| ao | Bai and Wang 2011 | Shaanxi Province, China | 393 mm | Silty loams | Orchard | | OC[h] | 0.275 | 125 | 0.3 | 0.1 | 0–10 | Exp. | 0 | 0.07 | 247.1 |

[a]Measurement method refers to the original property which was measured. All values have been converted into OC
[b]Organic matter (OM), total and effective acidity (determined by 1 M calcium acetate – Ca(CH3 COO)2 H2 O and 1 M KCl titulometric method, respectively),
[c]Unpublished data provided by Pringle for the publication of McBratney & Pringle (1999)
[d]Potassium bichromate titrimetric method
[e]Photocolorimetry
[f]Laboratory analysis was completed by the Soil Management Division – NIAST, RDA
[g]Redox-Electrode (Methrom Titroprocesador)
[h]Oil bath titration

**Table 21.5** Compilation of key properties for available nitrogen variograms

| | Reference | Location | Climate | Soil type | Land use | Timing | Measurement method | Study area (ha) | Sample size | Mean | Standard deviation | Depth (cm) | Model | Nugget | Partial sill | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| a | Liu et al. (2010) | Henan Province, Central China | Monsoon climate 14.6C, 680 mm | Sandy to medium clay loam | Crop | After harvest | Alkaline hydrolysable N (AN) | 4 | 111 | 75 | 14.3 | 0–20 | Spherical | 105.6 | 127.3 | 112.6 |
| b | Liu et al. 2008 | Henan Province, Central China | Monsoon climate 14.6C, 680 mm | Clay loam to loam | Crop | Before sowing | Alkalytic N (AN) | 87 | 81 | 70.6 | 10.3 | 0–20 | Linear | 110.46 | 0 | NA |
| c | Lopez-Granados et al. (2002) (site two) | Caracol, Southern Spain | | Vertic Xerochep | Crop | Before winter sowing | Nitrate | 6 | 84 | 23.2 | 10.2 | 0–10 | Exponential | 10 | 91 | 31.7 |
| d | Chatterjee et al. (2015) | West Bengal, India | Hot and humid | | Crop | After harvest | Available N | 81 | | 76.7 | 7.8 | 0–15 | Spherical | 17.38 | 45.26 | 43 |
| e | Shire 1997; cited in McBratney & Pringle (1999)[d] | Wyalkatchem, Western Australia | | Duplex | Crop | | Nitrate | 90 | 88 | 22.9 | 7.6 | 0–10 | Spherical | 22.14 | 36.86 | 281.432 |
| f | Lopez-Granados et al. (2002) site one | Monclova, Southern Spain | | Alfisol | Crop | Before winter sowing | Nitrate | 11.2 | 80 | 7.1 | 5.3 | 0–10 | Nugget | 27.2 | 0 | 0 |
| g | Cahn et al. (1994) 0.25 ha | Central Illinois | | Mollisol | Crop | | Nitrate | 0.25 | 200 | 6.2 | 3.7 | 0–15 | Experimental | 7 | 3 | 5 |
| h | Everett and Pierce (1996) | Michigan | | Loamy sand, sandy loam | Crop | | Nitrate | 22.6 | 60 | 6.2 | 2.2 | 0–30 | Spherical | 3.05 | 3.7 | 167.05 |

(continued)

**Table 21.5** (continued)

| | Reference | Location | Climate | Soil type | Land use | Timing | Measurement method | Study area (ha) | Sample size | Mean | Standard deviation | Depth (cm) | Model | Nugget | Partial sill | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| i | Tabor et al. (1985) | Arizona | | Haplargid/mollisol | Crop | | Nitrate | 13 | 49 | 13.6 | 4.2 | 0–20 | Linear | 6.66 | 11.12 | 200 |
| j | van Meirvenne and Hofman (1989) | Belgium | | Udifluvent | Horticulture | | Nitrate | 1 | 247 | 8.9 | 2.7 | 0–100 | Experimental | 2.25 | 4.25 | 25 |
| k | Wade et al. (1996) (pasture) | | | | Pasture | | Nitrate | | 86 | 0.8 | 0.8 | 0–10 | Experimental | 0.44 | 0.57 | 120 |
| l | Cambardella et al. (1994) | Iowa | | Udic/argic mollisols | Crop | | Nitrate | 10 | 72 | 7.2 | 1.3 | 0–15 | Spherical | 0.14 | 0.2 | 201 |
| m | Wade et al. (1996), (arable) | Warwickshire, England | | | | | Nitrate | | 81 | 0.7 | 0.5 | 0–10 | Experimental | 0 | 0.3 | 60 |

[a]Alkaline hydrolysable N was measured using the alkaline hydrolysis diffusion method
[b]Nitrate determined by colorimetry in SKALAR
[c]Available N content was determined by alkaline permanganate method as provided in Chatterjee et al. (2015)
[d]Unpublished data provided by Pringle for the publication of McBratney & Pringle (1999)

**Table 21.6** Compilation of key properties for total nitrogen variograms

| | Reference | Location | Climate | Soil type | Land use | Timing | Measurement method | Study area (ha) | Sample size | Mean | Standard devia-tion | Depth (cm) | Model | Nugget | Partial sill | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| a | Ganawa et al. (2003) | Sawah Sempadan, Malaysia | | Jawa, Teluk, Karang, Sempadan and Sedu | Crop | Before plant-ing | [a] | 2,300 | 120 | 4140 | 870 | 0–20 | Spherical | 100,000 | 700,000 | 460 |
| b | Yana et al. (2000) | Takatsuki, Japan | 15.8 °C, 1,240 mm | Clay loam | | After trans-plant-ing | Dry combustion | 0.5 | 91 | 3,100 | 449.5 | | Spherical | 30,000 | 270,000 | 35.5 |
| c | Yana et al. (2000) | Takatsuki, Japan | 15.8 °C, 1,240 mm | | Crop | After harvest | Dry combustion | 0.5 | 91 | 3,400 | 452.2 | | Spherical | 80,000 | 200,000 | 19.5 |
| d | Zhang et al. (2016) | Jiangsu Province, China | | | Crop | | | 7 | 136 | | | | Exponential | 0 | 180,000 | 39.08 |
| e | Shukla et al. (2004) | Gross-Enzersdorf, Austria | 510 mm, 10C | Loam to sandy loam | Crop | May | Kjeldahl method | 6.25 | | 1,328.6 | 381 | 0–15 | Spherical | 106,576 | 31,746 | 243.6 |
| f | Nouri et al. (2010) | Fesaran village, Esfahan | | Clay loam and loam | Horticulture | Before fertiga-tion | Nitrate | 87 | 60 | | | 0–30 | Spherical | 30,000 | 30,000 | 141.8 |
| g | Liu et al. (2008) | Henan Province, Central China | Monsoon climate 14.6C, 680 mm | Clay loam to loam | Crop | Before sowing | Kjeldahl method | 87 | 81 | 730 | 100 | 0–20 | Spherical | 2,000 | 9,000 | 274 |
| h | Ayoubi et al. (2007) | Golestan Province, Iran | | Fine, mixed, thermic, fluventic haploxerepts | Crop | Before sowing | Kjeldahl method | 1.8 | 101 | 1,300 | 110 | 0–30 | Gaussian | 600 | 10,000 | 23.99 |
| i | Chung et al. (2008) | Korea | 12.7C, 1,560 mm[b] | Coarse loamy | Crop | After harvest | [b] | 0.3 | 246 | 1,500 | 100 | | Exponential | 0 | 0 | 4.5 |

[a]Sulfuric-salicylic acid digestion method
[b]Laboratory analysis was completed by the Soil Management Division – NIAST, RDA

**Table 21.7** Compilation of key properties for phosphorus variograms

| | Reference | Location | Climate | Soil type | Land use | Timing | Measurement method | Study area (ha) | Sample size | Mean | Standard deviation | Depth (cm) | Model | Nugget | Partial sill | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| a | McBratney et al. (1985) | Narrabri, NSW, Australia | | Vertisol | Crop | | P (NaHCO3 soluble) | 1 | 386 | 129.6 | 58.8 | 0–7.5 | Gaussian | 152.85 | 7,489.55 | 109.64 |
| b | Chatterjee et al. (2015) | West Bengal, India | Hot and humid 1443 mm | | Crop/ horticulture | After harvest | Available P2O5 | 81 | | 172.4 | 82.4 | 0–15 | Spherical | 3,700.68 | 3,925.85 | 283 |
| c | Mondo et al. (2012) | Sao Paolo, Brazil | | | Crop | After harvest | P resin | 22 | 33 | 239.6 | 59.6 | 0–20 | Spherical | 1,484.69 | 2,030.1 | 89.9 |
| d | Cambardella et al. (1994) (pothole field) | Iowa, USA | | Udic/aquic mollisols | Crop | | P (bray no. 1) | 6.25 | 241 | 126 | 55.6 | 0–15 | Spherical | 596.9 | 2,839 | 71 |
| e | Delcourt et al. (1996) | Leefdaal, Belgium | | Silty | Crop | | P (colorimetric) | | | | | 0–25 | Gaussian | 310 | 850 | 74.5 |
| f | Cahn et al. (1994), 0.25 ha | Central Illinois, USA | | Mollisol | Crop | | P (bray no. 1) | 0.25 | 200 | 74 | 26.8 | 0–15 | Experimental | 390 | 760 | 50 |
| g | Pierce et al. (1995), (Plainwell) | Plainwell, USA | | Entisol, loamy sand | Crop | | P (not specified) | 22 | 174 | 124 | 32 | 0–20 | Spherical | 233 | 844 | 172 |
| h | Camacho -Tamayo et al. (2008) (site two) | Puerto Lopez, Colombia | 2,375 mm 27 C | Typic hapludox | Crop | Aug 04 | P (bray II) | 1.875 | 42 | 28.8 | 25.8 | 0–10 | Spherical | 2 | 660.5 | 38.4 |
| i | Ganawa et al. (2003) | Sawah Sempadan, Malaysia | | Jawa, Teluk, Karang, Sempadan and Sedu | Crop | Before planting | Available P NH4 | 2,300 | 120 | 50.2 | 22.5 | 0–20 | Spherical | 69 | 422 | 597 |
| j | Nolin et al. (1996) | Quebec, Canada | | Aquepts | Crop | | P (Melich III) | 10 | 130 | 52 | 18.5 | 0–15 | Exponential | 35.1 | 255.5 | 13 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| k | Chung et al. (2008) | Korea | | | Crop | After harvest | [c] | 0.3 | 246 | 119 | 15.5 | | Spherical | 17.8 | 210.3 | 4 |
| l | Pierce et al. (1995) Durand | Durand, USA | | Alfisol, fine loam | Crop | | P (not specified) | 16 | 165 | 35 | 21 | 5:20 | Linear | 223 | 163 | 294 |
| m | Camacho -Tamayo et al. (2008) (site one) | Puerto Lopez, Colombia | 2,375 mm 27 C | Typic haplustox | Crop | May-04 | P (bray II) | 1.875 | 42 | 11.1 | 14.2 | 0–10 | Linear | 154.4 | 262.9 | 373.4 |
| n | Frogbrook et al. (2002) (sampled 1998) | | | | | Before fertili-sation | | 16.5 | | | | | Exponential | 17.95 | 131.5 | 17.07 |
| o | Frogbrook et al. (2002) (sampled 1999) | | | | | | | 16.5 | | | | | Spherical | 54.58 | 66.61 | 54.9 |
| p | Frogbrook et al. (2002) (sampled 1997) | | | | | | | 16.5 | | | | | Spherical | 56 | 59.72 | 49.95 |
| q | Kristensen et al. (1995) (Riso) | Riso, Denmark | | Sandy loam/sandy clay loam | Crop | | Available P | 10.9 | 270 | | | 0–25 | Exponential | 0 | 110 | 60 |
| r | Shatar (1996) | Moree, Australia | | Vertisol | | | Available P | 15 | 114 | 18 | 1 | 15–30 | Spherical | 55 | 50 | 290 |
| s | Sidorova et al. (2012) | Northwestern Russia | | | Crop | | Available P[d] | | 72 | 484.9 | 65.6 | | Spherical | 11 | 93 | 63.7 |
| t | Pierce et al. (1995) (Adrian) | Adrian, USA | | Alfisol, loam | Crop | | P (not specified) | 10 | 74 | 23 | 9 | 0–5 | Exponential | 23.6 | 60.49 | 68 |
| u | Machado et al. (2007) | Uberlandia, Brazil | Tropical humid with dry season, | Red latosol, moderate clayey texture | Crop | | | 25 | | 12.4 | 9.1 | 0–20 | Linear | 82.33 | 0 | NA |
| v | Mulla (1993) | St. John, Washington, USA | | Silt loam (ultic haploxeroll) | Crop | | P (acetate extractable) | 8 | 172 | 15.2 | 7.7 | 0–30 | Spherical | 27.58 | 35.8 | 145 |

(continued)

**Table 21.7** (continued)

| | Reference | Location | Climate | Soil type | Land use | Timing | Measurement method | Study area (ha) | Sample size | Mean | Standard devia-tion | Depth (cm) | Model | Nugget | Partial sill | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| w | Rowlands 1998; cited in McBratney & Pringle (1999)[e] | Wyalkatchem, WA, Australia | | Duplex | Crop | | P (not specified) | 75 | 56 | 31.9 | 7 | 0–10 | Spherical | 22.32 | 28.72 | 414.604 |
| x | Kristensen et al. (1995) (Vindum) | Vindum, Denmark | | Sandy loam | Crop | | Available P | 10 | 302 | | | 0–25 | Exponential | 0 | 45 | 148 |
| y | Liu et al. (2008) | Henan Province, Central China | Monsoon climate 14.6C, 680 mm | Clay loam to loam, | Crop | Before sowing, | Available P[f] | 87 | 81 | 16.1 | 5.9 | 0–20 | Spherical | 13.4 | 22.59 | 337 |
| z | Lopez-Granados et al. (2002) (site two) | Southern Spain (Caracol) | | Vertic Xerochep | Crop | Before crop | Available P[g] | 6 | 84 | 11.3 | 5.6 | 0–10 | Exponential | 0.7 | 33.3 | 28.3 |
| aa | Lopez-Granados et al. (2002) (site one) | Southern Spain (Monclova) | | Alfisol | Crop | Before r crop | Bray extractable P[g] | 11.2 | 80 | 15.5 | 4.4 | 0–10 | Exponential | 0.6 | 18.6 | 27.4 |
| ab | Ayoubi et al. (2007) | Golestan Province, Iran | | Fine, mixed, thermic, fluventic haploxerepts | Crop | Before crop | Available P[h] | 1.8 | 101 | 27.2 | 1.3 | 0–30 | Spherical | 1.08 | 0.57 | 35.58 |

[a] Available P2O5 Olsen method by way of extracting 2.5 g of soil with 50 ml of 0.5MNaHCO3 (pH 8.5) for 30 min and determining the phosphorus in the extract by the L-ascorbic acid method
[b] Available P NH4F-HCl extraction method
[c] Laboratory analysis was completed by the Soil Management Division – NIAST, RDA
[d] Available P (the TsI-NAO modification of the Kirsanov method)
[e] Unpublished data provided by Pringle for the publication of McBratney & Pringle (1999)
[f] Available P Olsen extraction method using alkaline sodium bicarbonate as the extractant in a 20:1 ratio
[g] Bray extractable P measured by colorimetry using ascorbic acid-ammonium molybdate reagents
[h] Available P measured by colorimetry using ascorbic acid-ammonium molybdate reagents

**Table 21.8** Compilation of key properties for potassium variograms

| | Reference | Location | Climate | Soil type | Land use | Timing | Measurement method | Study area (ha) | Sample size | Mean | Standard deviation | Depth (cm) | Model | Nugget | Partial sill | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| a | Lopez-Granados et al. (2002) (site two) | Caracol, Southern Spain | | Vertic Xerochep | Crop | Before planting | Exchangeable K | 6 | 84 | 741 | 156 | 0–0.10 | Spherical | 0 | 15,210 | 54.6 |
| b | Lopez-Granados et al. (2002) (site one) | Monclova, Southern Spain | | Alfisol | Crop | Before planting | Exchangeable K | 11.2 | 80 | 468 | 117 | 0–0.10 | Exponential | 0 | 15,210 | 34.5 |
| c | Cahn et al. (1994) (0.25 ha) | Cemtral Illinois, USA | | Mollisol | Crop | | K (not specified) | 0.25 | 200 | 268.2 | 114.9 | 0–15 | Experimental | 5000 | 7500 | 50 |
| d | Pierce et al. (1995) (Adrian) | Adrian, USA | | Alfisol, loam | Crop | | K (not specified) | 10 | 74 | 210 | 71 | 0–5 | Exponential | 1850 | 4168 | 93 |
| e | Frogbrook et al. (2002) (sampled 1997) | | | Clay loam | | Before fertilisation | | 16.5 | 110 | | | | Spherical | 994.5 | 1831 | 55.09 |
| f | Chatterjee et al. (2015) | West Bengal, India | Hot and humid, 1443 mm | | Crop/ horticulture | After harvest | Available K2O | 81 | | 134.8 | 51.9 | 0–15 | Exponential | 1864.51 | 923.4 | 55 |
| g | Chung et al. (2008) | Korea | 12.7C, 1560[b] | Coarse, loamy, mixed, non-acid, mesic | Crop | After harvest | | 0.3 | 246 | 269.1 | 27.3 | | Gaussian | 304.2 | 2281.5 | 32.9 |
| h | Frogbrook et al. (2002) (sampled 1998) | | | | | Before fertilisation | K[c] | 16.5 | | | | | Circular | 1121 | 1266 | 57.71 |

(continued)

**Table 21.8** (continued)

| | Reference | Location | Climate | Soil type | Land use | Timing | Measurement method | Study area (ha) | Sample size | Mean | Standard deviation | Depth (cm) | Model | Nugget | Partial sill | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| i | Frogbrook et al. (2002) (sampled 1999) | | | | | Before fertilisation | | 16.5 | | | | | Penta-spherical | 1050 | 1034 | 79.03 |
| j | Nanni et al. (2011) | Sao Paulo state, Brazil | Mesothermic climate | Oxisols, entisols, alfisols, ultisols, inceptisols and mollisols | Crop | | | 184 | 184 | 61.3 | 44.6 | | Spherical | 706.18 | 1373.56 | 353 |
| k | Pierce et al., (1995) (Plainwell) | Plainwell, USA | | Entisol, loamy sand | Crop | | K (not specified) | 22 | 174 | 121 | 35.9 | 0–20 | Spherical | 887 | 391 | 157 |
| l | Ferraz et al. (2012) (sampled 2008) | Tres Pontas, Brazil | Mild tropical altitude | Red-yellow latosol | Crop | | K Mehlich 1 | 22 | 48 | 7.1 | 6.5 | 0–20 | Spherical | 0 | 1268.37 | 437 |
| m | Liu et al. (2010) | Henan Province, Central China | Monsoon climate 14.6C, 680 mm | Sandy to medium clay loam | Crop | After harvest | Available K[d] | 4 | 111 | 161.4 | 30.8 | 0–20 | Spherical | 435 | 744.1 | 312.4 |
| n | Silva et al. (2003) | Santa Maria, Brazil | | Ultisol dystrophic hapludalf | Crop | Before sowing | Available K (flame photometry) | 0.3 | 194 | 111 | 31.9 | 0–20 | Gaussian | 527 | 619 | 16.6 |
| o | Pierce et al. (1995), (Durand) | Durand, USA | | Alfisol, fine loam | Crop | | K (not specified) | 16 | 165 | 97 | 31 | 5–20 | Spherical | 302 | 833 | 174 |
| p | Delcourt et al. (1996) | Leefdaal, Belgium | | Silty | Crop | | K (AES) | | | NA | NA | 0–25 | Spherical | 425 | 565 | 149.7 |
| q | Rowlands 1998; cited in McBratney & Pringle (1999)[b] | Wyalkatchem, WA | | Duplex | Crop | | K (not specified) | 75 | 56 | 59.1 | 24.7 | 0–10 | Spherical | 185.17 | 581.23 | 800 |
| r | Camacho-Tamayo et al. (2008) (site two) | Puerto Lopez, Colombia | 2375 mm 27C | Typic hapludox | Crop | Aug 04 | K[e] | 1.875 | 42 | 74.1 | 15.6 | 0–10 | Exponential | 182.52 | 349.83 | 366.6 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| s | Machado et al. (2007) | Uberlandia, Brazil | Tropical humid with dry season | Red latosol, moderate clayey texture | Crop | | K[f] | 25 | 121 | 79 | 21.5 | 0–20 | Linear | 466.4 | 0 | NA |
| t | Kristensen et al. (1995) (Riso) | Riso, Denmark | | Sandy loam/sandy clay loam | Crop | | Available K | 10.9 | 270 | | | 0–25 | Exponential | 0 | 389 | 129 |
| u | Kristensen et al. (1995) (Vindum) | Vindum, Denmark | | Sandy loam | Crop | | Available K | 10 | 302 | | | 0–25 | Exponential | 0 | 377 | 25 |
| v | Ferraz et al. (2012) (sampled 2007) | Tres Pontas, Brazil | Mild tropical altitude | Red-yellow latosol | Crop | | K Mehlich 1 | 22 | 54 | 11.5 | 12.5 | 0–20 | Exponential | 0 | 365.82 | 165 |
| w | Liu et al. (2008) | Henan Province, Central China | Monsoon climate 14.6C, 680 mm | Clay loam to loam, and the soil is slightly alkaline (pH, 7.7) | Crop | Before sowing | Available K (AK)[d] | 87 | 81 | 105.9 | 14.3 | 0–20 | Spherical | 66.9 | 149.2 | 345 |
| x | de Souza et al. (2010) (site one) | Araras, Southeast Brazil | Wet summer, dry winter | Oxisol (typic haplustox) | Crop | Fall of 2003 | | 20 | 80 | 3.2 | 1.3 | 0–20 | Spherical | 26.1 | 103.9 | 185 |
| y | Sidorova et al. (2012) | Northwestern Russia | | | Crop | | Exchangeable K[g] | | 72 | 202.5 | 36.2 | | Exponential | 7 | 106 | 72.8 |
| z | Ayoubi et al. (2007) | Golestan Province, Iran | | Fine, mixed, thermic, fluventic haploxerepts | Crop | Before sowing | Available K[h] | 1.8 | 101 | 334.6 | 8.1 | 0–30 | Spherical | 17.16 | 62.4 | 93.92 |
| aa | Camacho-Tamayo et al. (2008) (site 1) | Puerto Lopez, Colombia | 2375 mm 27C | Typic haplustox | Crop | May 04 | K[e] | 1.875 | 42 | 70.2 | 7.8 | 0–10 | Nugget | 60.84 | 0 | 0 |

(continued)

**Table 21.8** (continued)

| | Reference | Location | Climate | Soil type | Land use | Timing | Measurement method | Study area (ha) | Sample size | Mean | Standard deviation | Depth (cm) | Model | Nugget | Partial sill | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ab | Thompson et al. (2004) (site two A) | Alabama, USA | | | Crop | January | | 0.2 | 124 | | | 22 | Exponential | 0.1 | 55.1 | 228.3 |
| ac | Thompson et al. (2004) (site two B) | Alabama, USA | | | Crop | January | | 0.4 | 58 | | | 22 | Spherical | 23.16 | 27.52 | 299 |
| ad | de Souza et al. (2010) – (site two) | Araras, Southeast Brazil | Wet summer, dry winter | Oxisol (typic haplustox) | Crop | Fall of 2004 | | 22 | 90 | 3.7 | 1.9 | 0–20 | Exponential | 0.9 | 3.2 | 121 |
| ae | Thompson et al. (2004) (site one) | Alabama, USA | | | Crop | September | | 0.4 | 71 | | | 11 | Spherical | 0.01 | 0.06 | 295.2 |
| af | Thompson et al. (2004) (site three) | Alabama, USA | | | Crop | September | | 0.4 | 48 | | | 11 | Spherical | 0 | 0.03 | 160.4 |

[a]Exchangeable K atomic absorption spectrophotometry (AAS)
[b]Unpublished data provided by Pringle for the publication of McBratney & Pringle (1999)
[c]Laboratory analysis was completed by the Soil Management Division – NIAST, RDA
[d]Available K (AK) neutral ammonium acetate extraction method
[e]K extraction with ammonium acetate pH 7.0
[f]HCl 0,05 mol L-1 + H2SO4 0,025 mol L-1
[g]Exchangeable K TsI-NAO modification of the Kirsanov method
[h]Available K extraction with ammonium acetate (1 N)

#### 21.5.1.2 Total Sill

Between studies the total sill (nugget plus partial sill) changes by several orders of magnitude for each property. As expected, this variability is the least pronounced for bounded properties (pH, OM %, sand % and clay %) and much more pronounced for micronutrients, which vary by around three to five orders of magnitude.

Variability in total sill is similar to that observed by McBratney and Pringle (1999). Inspection of the summary tables (Tables 21.1, 21.2, 21.3, 21.4, 21.5, 21.6, 21.7 and 21.8) indicates that for the majority of soil properties, the range in the total sill is similar for the variograms collected by McBratney and Pringle (1999) and the more recently collected properties. The maximum variability reached within 1 km has remained within an order of magnitude for all properties. For soil pH, organic carbon and potassium, the maximum variability found in the more recent literature search is two to three times greater than the maximum variability found in the literature reviewed by McBratney and Pringle (1999). The other properties have a very similar maximum.

#### 21.5.1.3 Nugget

Like McBratney and Pringle (1999), we find wide variability (several orders of magnitude) in the nugget parameter. McBratney and Pringle (1999) suggest that this variability is largely due to the strong effect of sampling design on the nugget. A variogram can only model the spatial structure that is detectable by the sampling design. In general, the wider the spacing, the more spatial variability will be attributed to the nugget component of the model. If the survey spacing is wider than the spatial structure, the variogram will appear as a pure nugget model. A wider support and the use of aliquotting will reduce the 'noise' in the data and decrease the nugget. It has been often proposed, and is quite likely, that the majority of soil properties would have more than one layer of soil structure. The differences in estimated nugget likely reflect both the underlying differences in spatial structure at the field scale and the capacity of different survey designs to capture this variability.

#### 21.5.1.4 Range

Like the lag and the sill, the range estimated by the theoretical variogram will be strongly affected by the sampling design. As the lag increases, the confidence interval around the variance increases (Oliver and Webster 2014). Precision agriculture surveys are typically conducted over areas from a few hectares to a few hundred hectares which limits the extent of spatial variability they can capture. Despite this, the majority of variograms fit from precision agriculture studies are bounded. The modelled range and sill can be thought of as the 'local sill' and 'local range' associated with the particular extent and spacing of that survey. It is very likely that if the extent of the survey was increased, another degree of variability would be found. It is critical to consider the potential effect of both the extent and the spacing on the range when considering precision agriculture studies and how their findings may inform your own work.

## 21.5.2 Field Scale Soil Variograms: Methodological Differences

### 21.5.2.1 Survey Design

Another substantial difference between the survey designs was whether or not aliquott ing was used. This is particularly significant when comparing these spatial studies because some studies model the range at distances that other studies were combining soil at. This is typically done for samples taken within 1 m of each other. This practice is likely to reduce the nugget (or white noise) and also to reduce any short-term spatial trends which might be occurring.

There is significant variation in the survey design which may influence the mapping of spatial variability. Nested designs are better placed to capture spatial trends across a variety of scales than designs with even spacing; however, because of the additional costs associated with these, they are less common.

### 21.5.2.2 Model Fitting Process

Oliver and Webster (2014) wrote an explanatory piece of work, describing the best methods for soil scientists to model variograms for kriging. They also described common mistakes made by soil scientists when calculating variograms. The majority of papers we assess do not follow all of Oliver and Webster's recommendations for reporting methods. This makes it difficult to assess how well a fitted variogram captures underlying spatial variability. Few papers report summary statistics for a variety of models, and few papers present variogram clouds to illustrate the utility of the fit. This does not necessarily mean that the fitted models are not accurate, but it does make it difficult to assess the model.

Another point worth considering is the possibility that trends are being overfitted. Perhaps some of the models presented in this chapter would have been better represented by a nugget. These issues around model quality are not new, but a degree of caution is required when interpreting the results.

The more recent literature has included studies which have found much lower values for the total sill for several soil attributes. For clay the lowest value found for the total sill is two orders of magnitude lower than the lowest value reported by Petit and McBratney. Sand is one order of magnitude lower. Some modelled variograms occur over a very tiny range of variability relative to the magnitude of the property they are measuring. Whether it is necessary or feasible to model a spatial structure of less than 1% for soil texture properties is questionable.

#### 21.5.2.3 Measurement Methods

The properties we have included here are commonly measured soil properties with known agronomic implications. However, measurement of these properties is rarely simple or consistent. Differences in measurement methods and differences in which component of the property is being measured will influence both the shape and magnitude of the variogram.

pH is an extremely commonly measured property. However, within the studies we have assessed, there are differences in the solution, the dilution rate and the equipment used to measure the pH. This problem becomes more complex when considering more difficult-to-measure properties such as potassium and phosphorus. Different studies have used different extractants to target different fractions for these nutrients.

The variogram is affected by the distribution of the property it is being calculated for. The variograms calculated for potassium and phosphorus show the greatest differences in total sill. We expect that this is because the target of the measurements varies as well as the measurement method used.

Some articles were found which estimated total carbon or inorganic carbon. However, there were relatively few such studies, so we have not included them here. We have included studies which measured organic matter as a proxy for organic carbon. We converted these using the van Bemmelen factor (1.724). Pribyl (2010) illustrates that an accurate conversion factor for different soils can vary from 1.4 to 2.5. Error in the conversion will be small relative to the overall spread of the variograms.

### *21.5.3 Field Scale Soil Variograms: A Compilation*

Figures 21.2, 21.3, 21.4, 21.5, 21.6, 21.7, 21.8. and 21.9. provide a visual compilation of field scale variograms for each of the soil properties initially examined by McBratney and Pringle (1999). We include both the original variograms used by McBratney and Pringle and variograms published since then. We only include variograms which were calculated from untransformed data and which were based on physical observations (i.e. not from remotely observed data). The black bold lines represent the average variogram (Sect. 21.7). Tables 21.1, 21.2, 21.3, 21.4, 21.5, 21.6, 21.7 and 21.8 correspond to each figure and include reference details and key parameters for each variogram. Because of the wide range of values of the source variograms, the scales used in the figures cannot include all of them, and some low sill variograms have not been included. We include the details in the tables for completeness, but suspect that they are unlikely to provide useful information. The figures affected and the number of source variograms not included are pH 1, carbon 3, total nitrogen 1 and potassium 2.

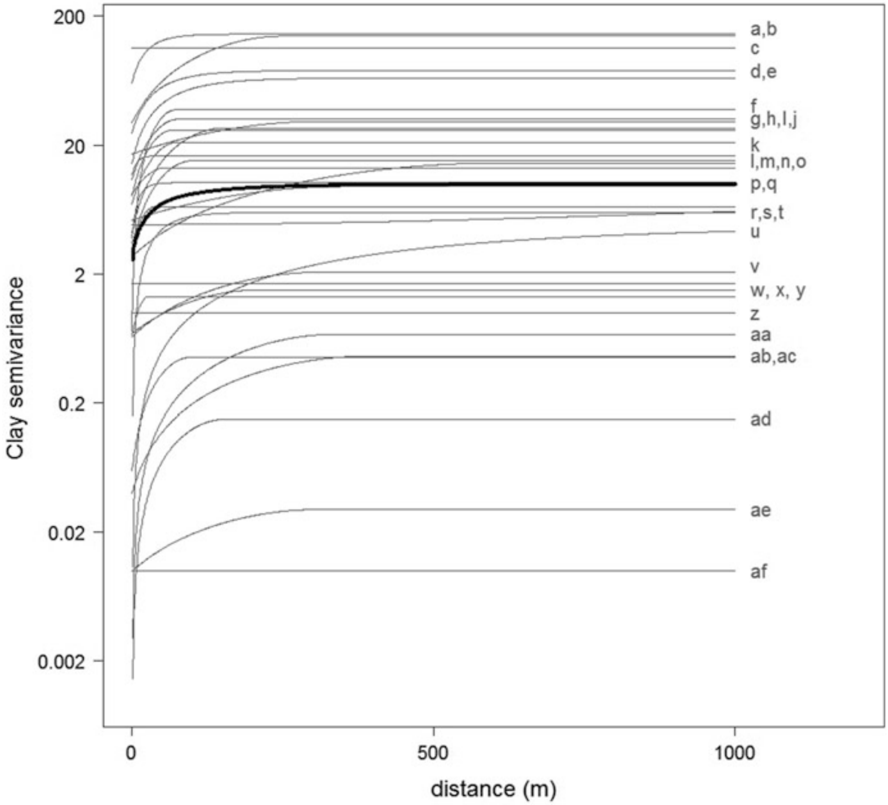


**Fig. 21.2** Compilation of field scale variograms for clay. The *bold black line* represents the average variogram. Summary details and references for each variogram (*a*–*ag*) are given in Table 21.1

## 21.6 Estimation of the Variogram from Proportional Variograms

McBratney and Pringle (1999) observe a strong relationship between mean squared and variance for several soil properties and develop a method for estimating a 'proportional variogram'. This method has the advantage of capturing the much higher levels of variability that tend to occur when the mean values of the property are extreme. Similar to McBratney and Pringle (1999), we find that some soil properties (phosphorus, nitrogen, potassium and carbon) appear to have a strong linear relationship between the mean and the standard deviation. This could imply that the calculation of a proportional variogram would be useful for these properties. However, closer interrogation reveals that this relationship is largely driven by high leverage points. It is not possible to fit a robust curve to link the mean and standard deviation. Proportional variograms are based on the relationship between the mean

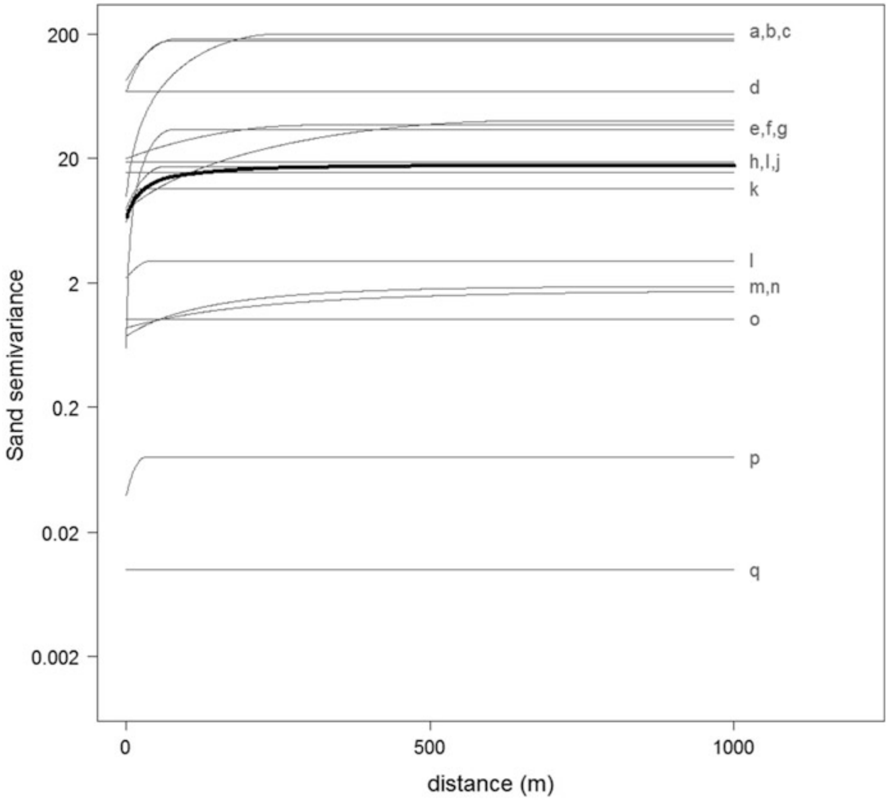


**Fig. 21.3** Compilation of field scale variograms for sand. The *bold black line* represents the average variogram. Summary details and references for each variogram (*a*–*r*) are given in Table 21.2

and the variance. Because we cannot be confident about this relationship, it is not prudent to calculate proportional variograms.

**We advise against the use of proportional variograms as an estimate for variability and as such do not update** McBratney and Pringle's (1999) **estimates of proportional variograms.**

## 21.7 Estimation of the Variogram from Average Variograms

McBratney and Pringle (1999) calculate average variograms for seven soil properties. These average variograms are calculated from the sample of variograms they compile. The fourth root transform of each approximated by the spherical model is taken and then backtransformed. Exponential or spherical models are fitted.

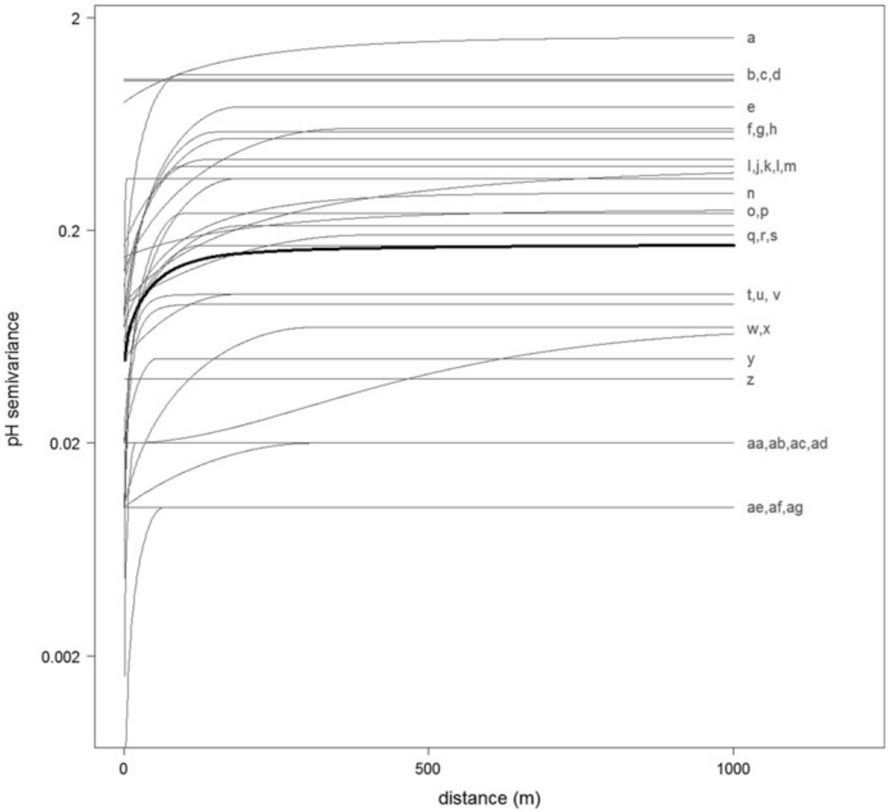


**Fig. 21.4** Compilation of field scale variograms for pH. The *bold black line* represents the average variogram. Summary details and references for each variogram (*a–ag*) are given in Table 21.3

McBratney and Pringle (1999) note the broad spread of variability in the variograms they collected and suggest that this might make the 'average' variograms less useful. Despite this, they suggest that the average variogram is a useful starting point where no other information is available. Kerry and Oliver (2003) find evidence that average variograms can be useful for prediction when parent material and soil forming factors are similar, but emphasise that they do not expect a global average variogram to provide much useful information.

We do not believe a global average provides useful information for predictive purposes. However, as McBratney and Pringle (1999) suggested, the average variogram does provide a useful reference for those interested in soil variability. We produce average variograms for illustrative purposes (by averaging the fourth root transform of each variogram at finely spaced intervals and then plotting the backtransformed values), but we do not fit these with a functional form.

As suggested by McBratney and Pringle (1999) and illustrated by Kerry and Oliver (2004), the concept of the average variogram has the most use for prediction

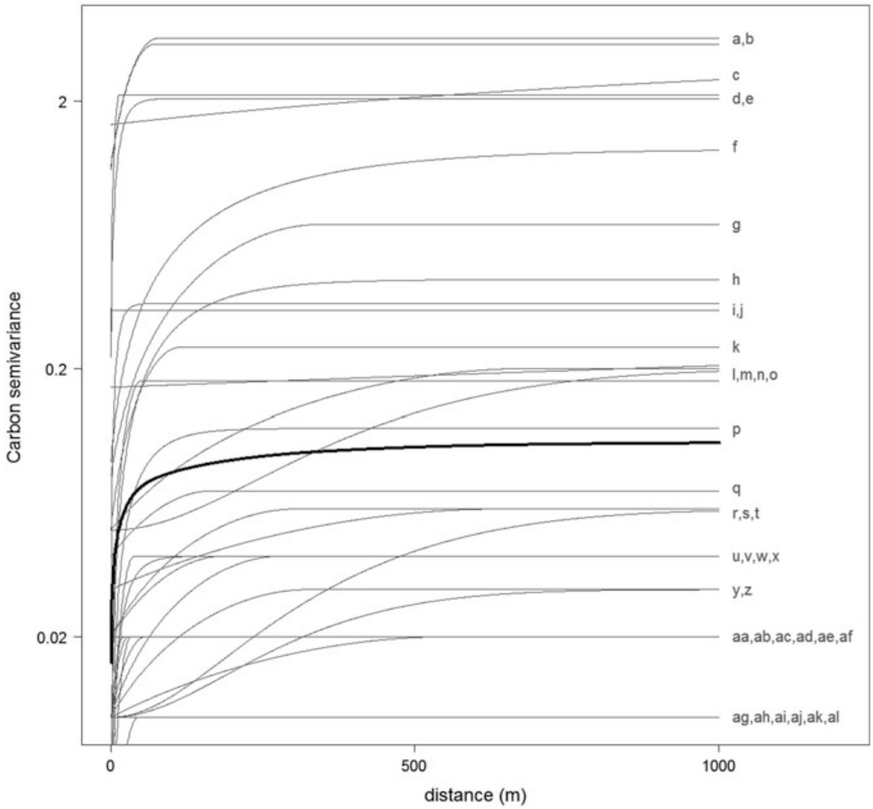


**Fig. 21.5** Compilation of field scale variograms for carbon The *bold black line* represents the average variogram. Summary details and references for each variogram (*a–al*) are given in Table 21.4

when it is calculated from a select subset of existing variograms. The diversity of climate regimes, soil types and land use for which field scale variograms have been calculated means that discretion is essential in the selection process. Differences in sampling regime, soil measurement protocols and geostatistical methods add another layer of complexity that needs to be navigated in appropriate selection. We discuss these issues further in the next section.

**We advise against the use of the 'global average' variogram as an estimate of local soil variability. Instead, where suitable variograms are available, an average of variograms with similar conditions is taken. Discretion and expert knowledge will need to be used in this selection process. The process outlined by** McBratney and Pringle (1999) **for calculation of an average variogram can be followed.**

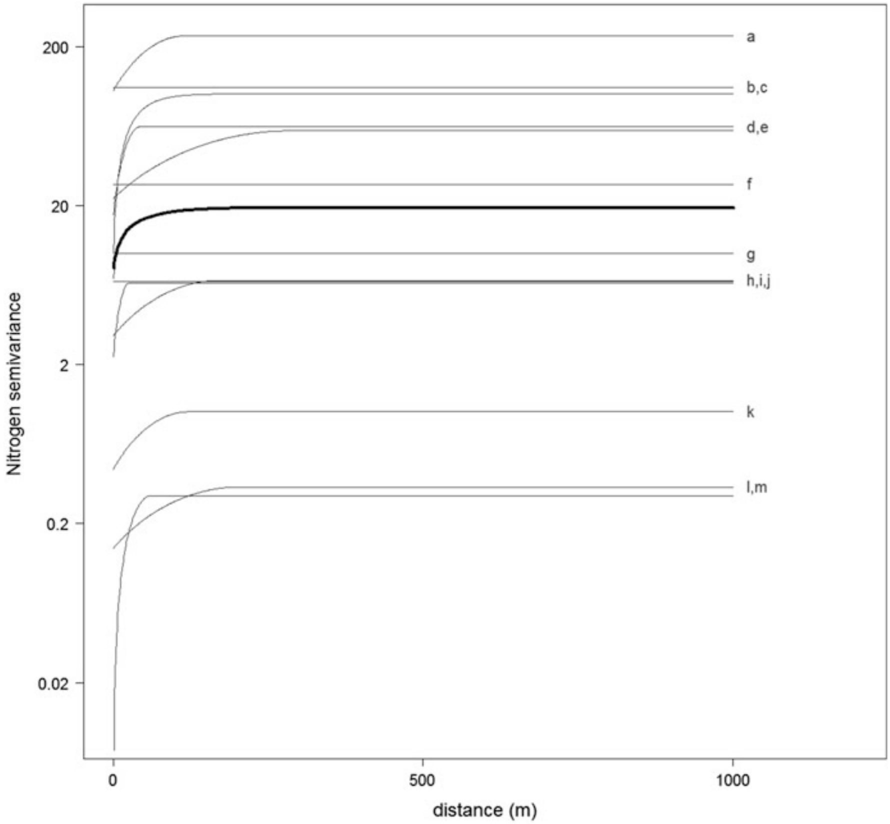


**Fig. 21.6** Compilation of field scale variograms for available nitrogen. The *bold black line* represents the average variogram. Summary details and references for each variogram (*a*–*m*) are given in Table 21.5

## 21.8 Ancillary Information

Kerry and Oliver have written several papers investigating the potential of using cheaper more densely available ancillary information to supplement expensive and sometimes sparse soil survey data. In 2004, they compared the spatial structure of a number of ancillary data sources to the spatial structure of a number of fixed soil properties. They found that variograms calculated from aerial colour photographs of 3.4 m ‘sampling density’ can estimate range with sufficient accuracy to helpfully guide sampling density of the soil survey. Kerry and Oliver (2008) paper extends the use of ancillary information to kriging. They suggest that the primary requirement for using data is that the ancillary variogram has a similar sill-to-nugget ratio to the property being studied.

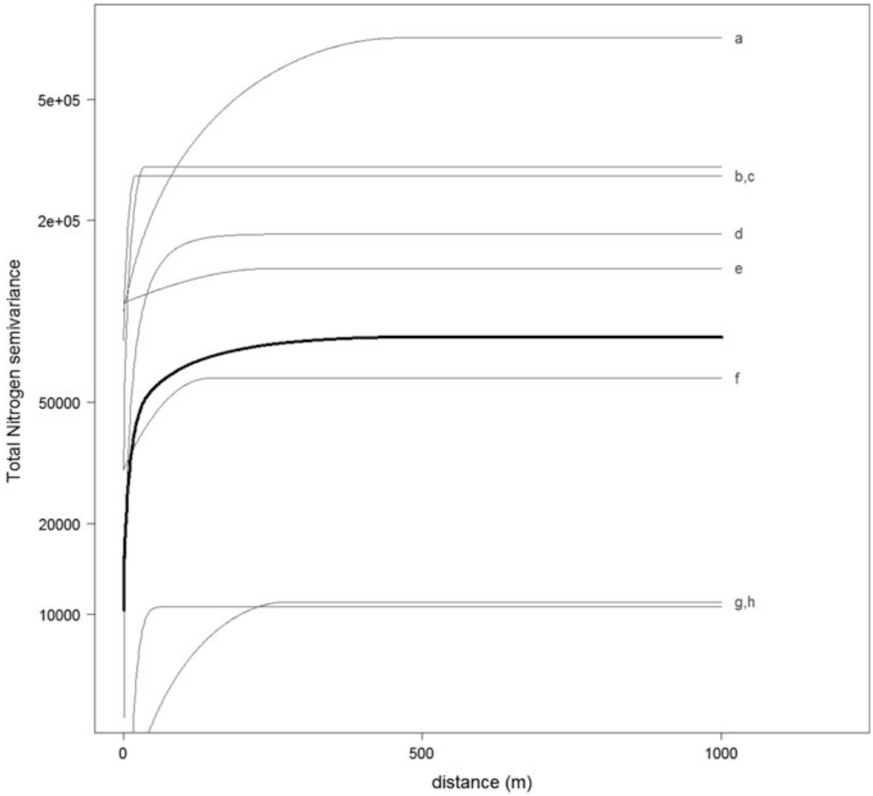


**Fig. 21.7** Compilation of field scale variograms for total nitrogen. The *bold black line* represents the average variogram. Summary details and references for each variogram (*a*–*h*) are given in Table 21.6

**Where it is available, ancillary information can be a useful source of information. Care must be taken in the selection of appropriate ancillary information. It may be useful to consult a range of ancillary variables.**

## 21.9 Expert Knowledge

Truong et al. (2013) propose the use of expert knowledge as a means to estimate the variogram when there are not enough observations to calculate a reliable variogram using geostatistics. They point to an increasing realisation from other disciplines that experts' knowledge provides a useful source of information that can be incorporated into statistical models. Truong et al. (2013) also suggest that expert knowledge may be useful when there is no data available or even when the available data for some reason are unreliable or unsuitable.

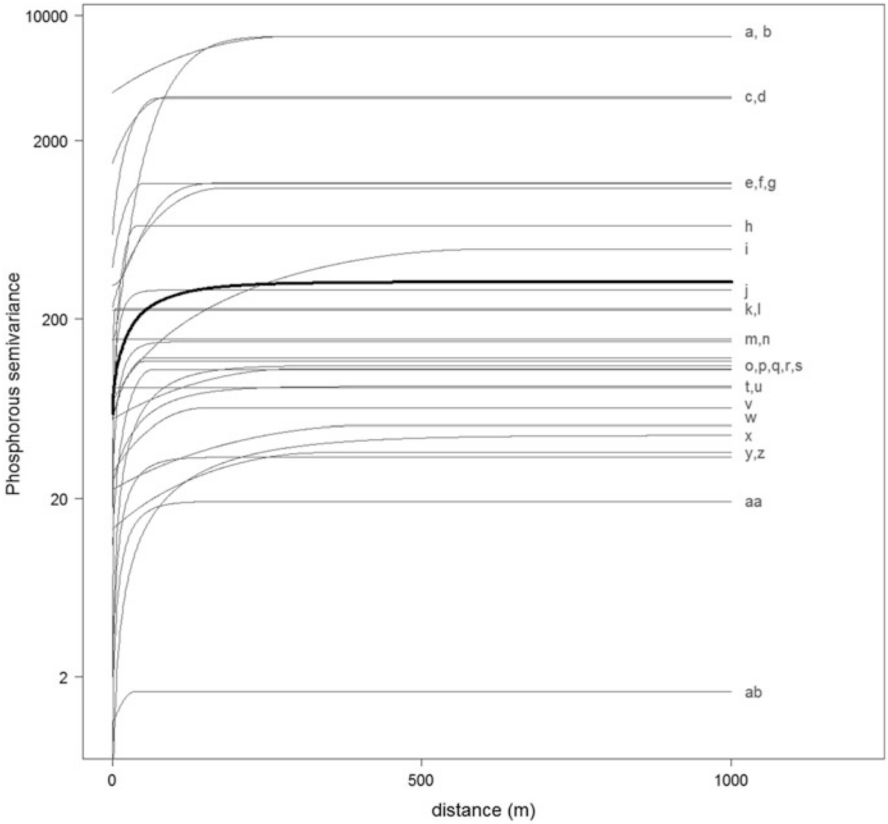


**Fig. 21.8** Compilation of field scale variograms for phosphorus. The *bold black line* represents the average variogram. Summary details and references for each variogram (*a*–*ab*) are given in Table 21.7

Truong et al. (2013) propose a strict methodology for eliciting knowledge from experts in order to construct a variogram. Their methods are designed to avoid bias. This process is still in the prototype stage. Currently, those seeking to supplement data with expert knowledge will not be able to avoid some bias. However, in many cases, subjective expert knowledge may be the best available option.

Even when there are data available, a degree of subjectivity will be required to assess the usefulness and representativeness of these data. Where possible, it will obviously be preferred that these subjective decisions are informed by those with expertise in the area of interest (geographical or topical).

**We strongly encourage the use of expert knowledge in the selection of appropriate datasets for the modelling of spatial variability. Where datasets are unavailable or deemed inappropriate, it may be necessary to rely entirely on expert knowledge to estimate the variogram. Eventually, it may be possible**

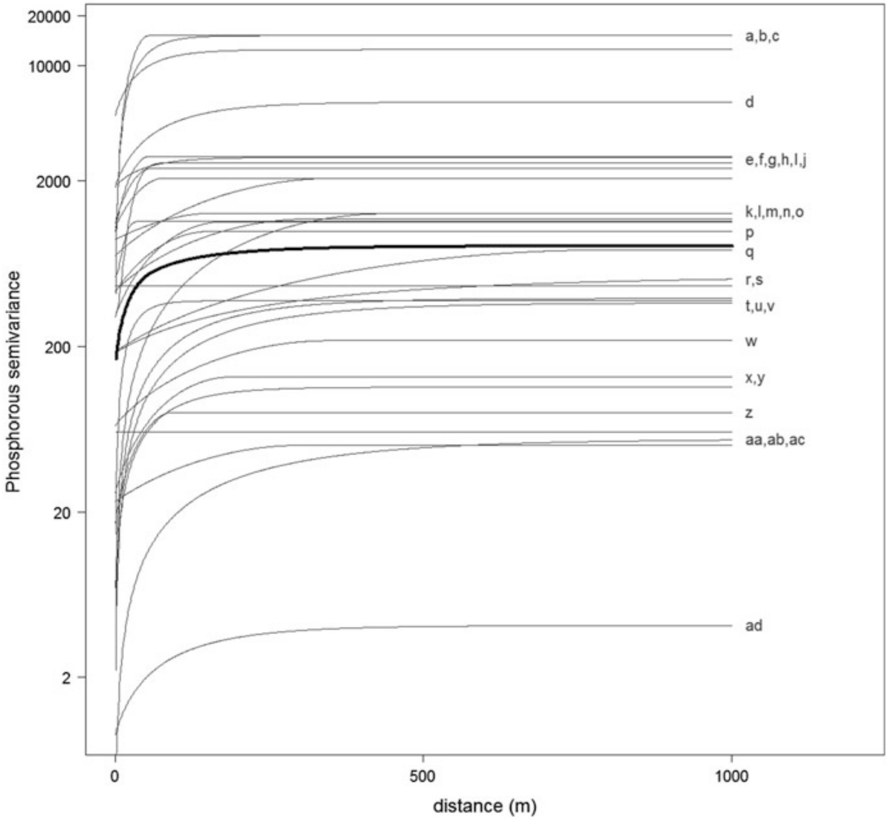


**Fig. 21.9** Compilation of field scale variograms for potassium. The *bold black line* represents the average variogram. Summary details and references for each variogram (*a*–*ad*) are given in Table 21.8

**to elicit expert knowledge using a formal process such as that described by** Truong et al. (2013).

## 21.10 Quick Variograms

There may be situations when ancillary information, variograms from literature or even expert knowledge are unavailable or unreliable. In these cases, we would like to propose the following sampling approach that can be used to estimate a rough variogram at very low cost. The method proposed will necessarily be imprecise, but is a better alternative than not having any information. We anticipate that this method would be particularly useful in cases where alternative sources of information are available but unreliable.


**Fig. 21.10** Sampling approach for estimating a 'rough' variogram. Here, it is shown that sampling is recommended in eight locations (four widely spaced points, each with a closely spaced pair, i.e. *A-B*, *C-D*, *E-F* and *G-H*)

We suggest sampling in eight locations (four widely spaced points, each with a closely spaced pair as per the diagram shown in Fig. 21.10). Obviously, the sampling design will be affected by the shape of the field. We advise that sampling occurs as close to the boundaries as possible while avoiding the edge effect.

In Fig. 21.10, one can calculate four bin sizes.

Close spacing (proxy for nugget): four pairs A-B, C-D, E-F, G-H
Maximum spacing (proxy for sill): eight pairs (A-G, A-H, B-G, B-H, C-E, C-F, D-E, D-F)
Intermediate spacing 1: eight pairs A-C, A-D, B-C, B-D, E-G, E-H, F-G, F-H
Intermediate spacing 2: eight pairs A-E, A-F, B-E, B-F, C-G, C-H, D-G, D-H

The close spacing (the close pairs) can be used as a proxy for the nugget, and the maximum spacing (the diagonals) can be used as a proxy for the total sill.

If the nugget and the sill are similar, we can assume that the appropriate model is the nugget model.

If the nugget and the sill are different, we will need to estimate the range and select a model for the variability.

There is no obvious proxy for the range that can be calculated from a small number of data points.

The two intermediate spacings may be useful to indicate where the range should occur. If they are similar to the total sill, then the range should be less than the intermediate spacings. If they are smaller than the total sill, then the range should be greater than the intermediate spacings.

We suggest that the intermediate spacings be used to determine the limits of where the range could occur. The range should then be taken as the halfway point between the limits.

For example, if the smallest intermediate bin has a variance similar to the sill, then we should set the range to be equal to the halfway point between the nugget and the smaller intermediate bin. If both of the intermediate bins have variances smaller than the sill, we should set the range to be equal to halfway between the total sill and the intermediate bin.

Modelling a range larger than the maximum separation distance is always unlikely in variograms, because of the tendency of models to break down beyond half of the field extent. We do not think that unbounded models (i.e. ranges greater than the maximum separation distance) are necessary to consider here.

**Quick variograms are not able to provide a precise estimation of soil variability. Their primary and important advantage is that they are calculated from data for the property of interest in the location of interest. Quick variograms provide a useful source of information when either (i) there are no other sources of information available or (ii) for checking alternative sources of information against a reference point.**

## 21.11 Recommendations

- Where it is economically and practically feasible, the best practice for estimating variograms is to conduct a preliminary survey and then a comprehensive field survey at the spatial scales of interest.
- Where resources for field survey are limited, it is desirable to find a variogram for the same property which has been calculated for a similar soil type. This variogram may be useful as a source of information for survey design. It may also be possible to use this variogram for kriging. Due to the large variability in soil variograms calculated for each soil property, it is critical to use discretion in this selection process.
- If more than one existing variogram from a similar soil type is identified, the information from both should be used. An averaging process may be a useful way to combine this information. Alternatively, they could be used separately to provide a range of predictions.
- Ancillary information (such as that from aerial photographs) should be considered to estimate variograms for soil properties. It can be used for survey planning and for kriging. Care must be taken to ensure that these variograms have a similar nugget-to-sill ratio to the property of interest. If available, it is preferred to use information from soil survey over ancillary information.
- If it is not possible to find a variogram for a similar area, other options are available. For example, expert knowledge could be consulted. Consultation of expert knowledge may occur in a formal process-based manner or in a more informal way.
- Quick field surveys, with limited sampling, may provide a cost-effective way to estimate rough variograms where other information is unavailable. These

methods may also be useful when it is desirable to supplement information with observations directly from the field.
- Variograms are useful for designing detailed sampling surveys for agricultural and environmental purposes.

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