THE NETHERLANDS SOIL SAMPLING PROGRAM

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ABSTRACT

Soil data users in The Netherlands were inventoried for current and future data needs. Prioritized data needs were used to design the Netherlands Soil Sampling programme (NSSP) as a framework containing 3 groups of related projects: map upgrading, map updating and upgrading of pedotransfer functions. In each one group, the sampling design, performance criteria and optimal sample size were defined. This paper focuses on the upgrading of the existing soil map of the Netherlands at scale 1:50,000, and extensively treats the user inventory and the sampling strategy. The sampling design, performance criteria of the sampling and associated optimal sample size were obtained by statistical analysis of soil data available before the sampling. The Phosphate Sorption Capacity (PSC) was chosen as target variable to optimize sampling, because it dominated total cost per sample. A prior analysis of a performance criterion related to the sampling error of PSC resulted in a cost saving of 13% relative to total cost determined earlier by expert judgment. A posterior analysis showed that the set quality criterion was reached or better in 6 out of 7 cases. The NSSP resulted in a data base with soil data from 2,524 sample points selected by stratified random sampling, and a collection of 5,764 aliquots taken at these points. The NSSP has been showing its usage potential for various kinds of environmental studies and could be a sound future basis for a national scale monitoring program.

KEYWORDS

Sampling, upgrading, geostatistics, accuracy.

1. INTRODUCTION

Soil, as one of the most important natural resources, has been surveyed on a national basis in many countries, for a broad variety of planning purposes. The resulting national soil maps are an invaluable source of information for planning and evaluating land use and for many other soil-related activities at the national and regional scale. However, as a result of changes in socio-economic circumstances, the need for soil information has changed. In developed and densely populated countries there is an increasing pressure on rational and sustainable land use, and soil quality is generally recognized as a major environmental issue, fundamental to the food production chain, nature conservation and drinking water quality, for instance.

The changes in soil information needs are diverse. First, there is a growing demand for information with higher spatial resolution. As far as resources allow, this need can be covered by soil mapping at larger scales.

Second, there is a need for more quantitative, accurate and detailed description of the variation of soil properties within the mapping units of existing national soil maps. These maps are typically produced by the method of `free survey' (Steur, 1961). As point data collection in free soil survey is aimed at delineation of map-units and description of `representative' soil profiles, these point data are usually insufficient, both quantitatively and qualitatively, for detailed quantitative description of soil properties within map-units. Furthermore, using these data for derived maps may produce biased results (Finke et al., 1996). New soil sampling on a statistical basis is generally required to cover this kind of information need.

Third, a need has arisen for information on soil properties not presented on the existing soil maps. Generally, these are physical and chemical properties which can only be determined in laboratories and are therefore not included in most national soil surveys. Nevertheless, many of these properties became highly relevant in view of modern modeling practices and risk assessment. Obviously, such gaps can only be filled by new sampling efforts.

Country-wide statistical soil sampling has been set up in some countries, in response to changing demands for soil information. The first example is the United Kingdom where between 1979 and 1984 the Soil Survey of England and Wales created the National Soil Inventory covering the whole of England and Wales. Systematic sampling was applied in the form of a 5 km square grid with a total of about 6000 sampling sites at the grid nodes. At each site a composite sample was taken with a 2.5 cm diameter auger, consisting of 25 cores from a depth of 0 to 15 cm, at 4 m intervals within a

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20 m x 20 m square centered at the grid node (Oliver et al., 1996). Concentrations of 18 elements were determined, and kriging was used to create pixel maps of the concentrations (McGrath and Loveland, 1992). Oliver et al. (1996) used disjunctive kriging to create maps of the probability of exceeding a threshold.

In Denmark a country-wide soil sampling was carried out from 1993 till 1996, as the first campaign in a programme for monitoring heavy metals in Danish soils. Sampling was done in a regular grid with 393 sampling sites of 50 m^2 size. At each site a composite sample was taken with a 3 cm diameter cylindrical drill to a depth of 25 cm, consisting of 17 cores in a regular pattern within the site. Concentrations of 8 heavy metals were determined; median values for different combinations land use and soil type are given in Bak et al. (1997).

Country-wide statistical soil sampling in the USA is still in an initial stage. The USDA Natural Resources Conservation Service and the Iowa State University Statistical Laboratory have developed a three-phase strategy for random sampling from map-units of county soil maps, using a Markov chain design (Breidt, 1995). This was implemented and tested in a pilot study on the soil map of Crawford County (Abbitt and Nusser, 1995).

In The Netherlands a country-wide soil sampling program has begun in 1988, and the first campaign is now finished. We refer to it as the Netherlands Soil Sampling Programme (henceforth NSSP). The purpose of this paper is to describe the aims, organization, methods and major achievements of NSSP.

The paper is structured as follows: an outline, the aims, structure and organization of NSSP are presented in Section 2; the sampling strategy is discussed in Section 3. An overview of the resulting sample data-base and the sample collection is given in Section 4. The paper ends with some examples of statistics that have been generated from the available sample data (Section 5) and discussion and conclusions (Sections 6 and 7).

2. OUTLINE OF THE NETHERLANDS SOIL SAMPLING PROGRAM

2.1 Rationale Of The Program

When the soil map of The Netherlands at scale 1:50,000 was about to be finished, it was recognized by the Netherlands Soil Survey Institute (now amalgamated in Alterra) that:

- No reliable and objective information about the accuracy of the map was available.
- The usefulness of the map would be greatly enhanced if the map-units were provided with a quantitative and detailed description of the soil properties within them. Although the underlying soil classification is morphometric (de Bakker and Schelling, 1989), the map legend and the associated reports present mainly qualitative, rather broad descriptions.
- The available point data, as gathered during the survey and recorded on field forms, caused serious problems if they were to be used for map-unit description: bias in sample point selection, incompleteness and inconsistencies in recording, sometimes poor legibility of the forms.
- If the map-units were to be sampled for better descriptions, then that would not only give an opportunity to improve the measurement quality of the existing soil properties, but also to add new properties, known to be relevant for present users of the map. Amongst the most relevant properties were those necessary to make regional and national estimates of the Proportion of Phosphate Saturation. Also, at that time, the available data on soil water retention and soil hydraulic conductivity were insufficient to characterize all Dutch soils by pedotransfer functions with sufficient precision.
- Part of the information depicted on the map was outdated due to human impact on the landscape during and after the mapping took place. Denote that the mapping comprised a period of about 30 years. In the course of commissioned regional detailed (1:10,000) mapping projects, the soil drainage situation represented in the map legend of the 1:50,000 soil map via the water-table class, was found to have changed significantly.
- A case study by Brus et al. (1992) showed that, in our circumstances, upgrading the soil map was more cost-effective than revision by improving the delineations on the map.

For these reasons the Soil Survey Institute decided to set up a country-wide soil sampling program, which was to be partly financed by the Dutch Ministry of Agriculture but also by regional authorities and which was monitored by several stakeholders. This sampling program served three major purposes:

1. Updating the thematic layer with water table depth classes;
2. Obtaining a more precise set of pedotransfer functions, with complete geographic coverage, for soil water retention and hydraulic conductivity characteristics;
3. Upgrading the 1:50,000 soil map through more quantitative, detailed and comprehensive description of map-units.

The approach and results of the sampling program for purposes (1) and (2) have been described elsewhere, e.g. by Finke (2000) and Finke et al. (2004) for the update and re-mapping of the water-table class maps (1), and by Wösten et al. (1988, 1994, 2001) for the initial and upgraded pedotransfer functions. In this article, we therefore limit ourselves to purpose (3), though we will refer to the broader context when appropriate (sections 2.2 and 6).

2.2 Organization And Structure Of The Program

The stages that led to the soil sampling program are depicted in Figure 1. Three more or less independent lines of research that involved soil sampling were evaluated against the outcome of an user inventory in 1992. This user inventory and experiences obtained in try-out projects served as starting point for the design phase of the soil sampling program. The try-out projects are considered a part of the sampling program, though both the sampling design and sampled characteristics slightly differ from the later full-cover sampling program.

Figure 1 near here

2.2.1 Early experiences and try-out projects

Already in an early stage, it was decided that some form of random sampling would be employed, in order to avoid subjectivity in sample point selection and to enable valid statistical inference from the sample data (Section 3). Experience with random designs for soil sampling had been gained before in several projects, e.g. van Kuilenburg et al. (1982), de Gruijter and Marsman (1985), Wösten et al. (1985), Marsman and de Gruijter (1986), Kleijn et al. (1987) and Breeuwsma et al. (1989).

The first project was carried out in 1988-1990 (Visschers, 1993). The target area was the combination of the two map-units classified as Typic Haplaquods (*Veldpodzolgronden*) in fine sand or slightly loamy fine sand and water-table class V or VI. (See van Heesen (1970) for a description of the water-table classification.) This target area (1732 km^2) was sampled at 520 points, selected by Stratified Two-Stage Random Sampling. At each point a profile description was made through augering to a depth of at least 1.5 m. The data, including the geographical co-ordinates, were recorded on a Husky Hunter field computer. The following properties were measured or observed:

- Organic matter content, clay content, loam content and median grainsize of the sand fraction (M50) in each horizon;
- Rootable depth;
- Mean Lowest Water table and Mean Highest Water table (van Heesen, 1970);
- Land Use

The second project was done in 1989-1990 (Ebbers and Visschers, 1993). The target-area was the set of all 12 map-units classified as Typic Humaquepts (*Beekeerdgronden*) in fine sand and water-table class III. This area (763 km^2) was sampled at 608 random points. The same methods were used as in the first project, but additional properties were measured: phosphate, iron and aluminum content, humus form and bulk density.

2.2.2 User inventory

Soil data are used by a variety of researchers, authorities and stakeholders, and it was therefore important to know their data needs before defining sets of soil characteristics to be collected with public funding. These needs were identified in a series of 35 oral interviews with selected stakeholders amongst the soil data users in the Netherlands (Leeters et al., 1996). The interviews were taped and consisted of open questions regarding the (i) current usage intensity of soil data and maps, (ii) the area of use and (iii) future needs regarding soil data. The posing of open questions allowed for the identification of new uses, wishes and applications of soil data, whilst asking closed (“multiple choice”) questions might have resulted in a conservative vision on soil data collection. Each data user was first ask to identify different activities (“projects”) for which soil data were used. Then, for each activity, the questions related to the issues (i)..(iii) mentioned above were repeated. The answers to these questions were categorized along three axes:

1. Category of soil data. Example categories: Soil map 1:10,000; Basic soil physical data; Basic soil chemical data; pedotransfer functions.
2. Field of research. Example categories: Process-research studies; Environmental planning; Studies on variability in space and time.
3. Wishes regarding the soil data. Examples: Improvement of currency; Increase spatial density of observations; Increase data quality; New data types.

The results of the categorization were presented in 3 matrices, where in each cell the fraction of activities (frA) is represented to which the situation applies. Values apply to the summed up activities for all interviewed people. These matrices are combinations of the three abovementioned axes:

A. Category of data X Field of research. One row was added at the bottom of this matrix containing the fraction of activities relating to each category of data (SumfrA). The cell values in this matrix serve as indicators of the usage intensity of soil data.
B. Wishes X Field or research.
C. Category of data X Wishes. The cell values in this matrix serve as indicators of the urgency of the wishes.

To prioritize the wishes for each category of soil data, the usage intensity SumfrA from matrix A was multiplied with the urgency of the wishes from matrix C. This resulted in a matrix C' containing values between 0 and 1, scaled from 0 to 100, where higher cell values indicate an essential soil data category in combination with highly urgent wishes. The most important cells in this matrix (meta-priorities) are presented in Table 1. We assumed that the interviewed persons comprised a representative sample of the group of stakeholders and also assured that the counted activities did never coincide.

The most prioritized wishes were then specified in terms of individual soil characteristics by reviewing the interview data. Wishes which were not related to specific soil characteristics were prioritized as well and the most important wishes (Table 2) were taken into account in the design phase.

2.2.3 Design and operational phases

In the design phase, the program was organized as three series of sampling projects. One series of interrelated projects comprised the upgrading of the map-units with point data. Another series of projects comprised the update of the water-table class maps, which has been reported elsewhere (Finke, 2000; Finke et al., 2004). The third line of activities was the upgrade of the Staring series class pedotransfer function by purposive sampling, which has been reported as well (Wösten et al., 2001). These three series of projects required different approaches to the sampling: The upgrading of the map units would benefit most by a random sampling scheme (cf. §2.2.1). The update of the water-table class maps required a sampling scheme with much higher spatial density to allow mapping at detailed scale (cf. Finke et al., 2004). The update of the class pedotransfer function required purposive sampling to assure that the desired texture classes were actually encountered in the field. Stakeholders and funding sources also differed between the three series of projects. Therefore, no attempt was made to integrate these three programs, though the map updating projects benefited from the sampling of the map units. In the next sections, we confine ourselves to the interrelated map-unit upgrading projects.

After the first two try-out projects, the approach was evaluated (Leeters et al., 1996) and some revisions were made for the next projects (van het Loo, 1997, 1998; Visschers, 1997, 1998, 1999a, 1999b, 2000, 2002):

- Map-units were clustered according to water-table class (van Heesen, 1970) instead of soil taxa. This was done because the latter would lead to too many clusters and equally many projects to run.
- The sampling design was slightly changed for higher efficiency: within the strata Simple Random Sampling was applied instead of Two-Stage Random Sampling.
- The sample size was optimized using the method described by Domburg et al. (1994) and the data on phosphate saturation from the sample in map-units with water-table class III (cf. section 3.3). This showed that the sample sizes planned a priori on the basis of expert knowledge could be reduced.
- It was decided to collect an aliquot from every horizon or layer, and to store these aliquots for future chemical analyses.
- Some additional properties were measured according to the results of the user inventory.

Each project was carried out by one or two experienced soil surveyors; five surveyors in total were involved in the program. The entire program was organized as 11 sampling projects, each documented in a report, and resulting in a data base with detailed profile descriptions and horizon data, as well as a collection of aliquots. See Table 3 and Table 4 for global information on the projects.

From a statistical point of view, the collection of sample points from projects 1 and 2 can be regarded and analyzed as one sample, while those from projects 3-11 together form a second sample. In Section 3 these are described as Sample A and Sample B, respectively.

3. SAMPLING STRATEGY FOR UPGRADING SOIL MAP UNITS

3.1 General Issues

We decided to follow the design-based approach to sampling, i.e. we chose a classical sampling strategy, which is a combination of a random sampling design and inference based on that design (Cochran, 1977). Brus and de Gruijter (1997) discussed the choice between the design-based (or classical) and the model-based (or geostatistical) approach to sampling in soil science. The reasons to choose the design-based approach were:

- We wanted to estimate quantities like spatial means, fractions and variances within relatively large sub-areas, not at points or in small sub-areas with only a few sample points.
- The available budgets allowed only low sampling densities, with inter-point distances that generally are too large to exploit spatial auto-correlation in estimations via geostatistical modeling.
- We wanted the estimates and their standard errors to be independent of model assumptions that are hard to verify.

In each of the projects it was decided to stratify the clusters of map-units, according to the main domains of interest. In that way it was ascertained that at least for these domains sufficiently accurate estimates were obtained. The allocation of sample sizes to the strata was not aimed at the highest precision of estimates for the clusters of map-units as a whole, but rather to obtain useful estimates for each stratum.

The criteria used for stratification differ between the projects. This freedom was deliberately allowed, to enable optimal adaptation to expected spatial variations and to the relative importance of domains within the various clusters of map-units. See Cochran (1977) for a general statistical treatment of sampling techniques and de Gruijter et al. (2006) for a comprehensive review of spatial sampling strategies.

In principle, the target area consisted of all non-aquatic soil in The Netherlands outside the build up areas. However, soil that is heavily disturbed or covered locally by human activities is regarded as `non-soil', hence left outside the target-population. This is mainly roads, verges, ditches, buildings and beet or maize storage pits.

The random coordinates of the sample points were generated with a special GIS-based application, and plotted on topographic field maps. The points were localized in the field by pacing or measuring from one or two nearby objects shown on the field maps, e.g. roads, ditches, parcel boundaries and houses. Sufficiently accurate GPS facilities were not available to us at the time of the fieldwork. If, on inspection in the field, a sample point turned out to fall outside the target area, it was replaced by a random spare point.

3.2 Sampling designs

Sample A, from projects 1 and 2 (Figure 1, §2.2.1 and § 2.2.3), was generated by Stratified Two-Stage Random Sampling. It does not cover the entire target area of The Netherlands; it is limited to a cluster of 14 map-units, each with Typic Haplaquods or Typic Humaquepts differentiated at series level. For stratification the 14 map-units were divided into 6 groups of pedologically similar units. The final stratification was obtained by subdividing these groups by map sheet. So, all delineations on a given map sheet that belong to a given group of map-units form one stratum. (If the area of a stratum was smaller than 1 km^2, it was fused with an adjacent stratum.) A total of 131 strata were defined in this way. Details on the stratification can be found in Visschers (1993) and Ebbers and Visschers (1993). The intention of this was to create strata that are pedologically as homogeneous as possible and also geographically compact.

In the first stage, two map delineations were randomly drawn from each stratum, with replacement and probabilities proportional to their area. Prior to drawing, large delineations (> 1 km2) were divided into smaller sections, which were then treated in the same way as undivided delineations. In the second stage, 4 points were randomly selected within the delineations drawn in the first stage. If the same delineation was drawn twice, then 4 points were selected from it twice.

Sample B, from projects 3-11, was generated by Stratified Simple Random Sampling. It covers the entire target area of The Netherlands, including the target area of Sample A. As outlined in Section 2, all map-units were primarily clustered by water-table class. This acted as the primary stratification (Figure 2), with 9 strata: map-units with water-table class I through VII, respectively, plus one cluster of units with more than one water-table class (associations), and one cluster of units with no water-table class (located in the hilly Loess region in the Southern part of the Province of Limburg, where the regular water-table classes are irrelevant).

Each primary stratum was further divided into a number of secondary strata. The criteria for the secondary stratifications differed between the primary strata. The number of secondary strata and the defining criteria followed from two objectives: (i) to obtain pedologically homogeneous strata, and (ii) to obtain sufficiently accurate estimates in certain domains of interest, such as significant nature areas. In total 95 strata were defined (Tables 4 and 5). Details on the stratification and sample sizes allocated to the strata can be found in van het Loo (1997, 1998) and Visschers (1997, 1998, 1999a, 1999b, 2000, 2002).

Figure 2 near here

3.3 A Priori And Ad Posterior Analyses Of Sample Size In Design B

The user inventory indicated that the Phosphate Sorption Capacity (*PSC*) and the Phosphate Saturation Proportion (*PSP*) should be measured at all points of sample B. It was estimated that per sample point about 85% of the cost would be associated with the analyses for *PSC* and *PSP*. Therefore it was decided to base the analysis of sample size on these characteristics.

PSC is estimated for a soil profile by a pedotransfer function (Schoumans and Groenendijk, 2000), which was constructed for non-calcareous sandy soils:

$$PSC_l = \sum_{j=l}^{l} 0.5 \times (Al_{ox} + Fe_{ox})_j \times 7.1 \times T_j \times \rho_j \qquad (1.)$$

where *l* is the number of layers above the reference depth *r* (*r* being the minimal value of either the Mean Highest Water table (MHW) and 100 cm), Al_{ox} and Fe_{ox} are oxalate-extractable Aluminum and Iron (mmol/kg), 7.1 is a multiplication factor to obtain kg/ha P_2O_5, T_j is the thickness (cm) of layer *j* that is still above the reference depth *r* and ρ_i is the dry bulk density of this layer (g/cm^3). Below the MHW, under temporarily reducing conditions, Fe-II Phosphates have higher solubility and thus the contribution of Fe to sorption capacity is limited.

PSP is defined as the ratio of oxalate-extractable Phosphorus (expressed in kg P_2O_5/ha) and *PSC*. *PSC* is a stable soil property and *PSP* is a variable of the (historical and present) land use. As we wished to incorporate available information of various age to optimize sample size, we chose to base the optimal sample size estimation on *PSC* data only. *PSC* data available before the NSSP are summarized per water-table class in Table 6. This table also gives expert guesses by experienced surveyors of the supposedly needed sample size.

Following Domburg et al. (1994), we wanted to optimize the sample size a priori by analyzing the relation between the expected sampling error of the mean *PSC* as a function of sample sizes allocated to the strata. This method is based on semivariograms of the target variable (*PSC;* Table 6), and requires an elaborated stratification so that each map polygon in the sample domain is assigned to one stratum. For each stratum, the average semivariance is estimated by simulating a random sample of *m* locations inside the associated map polygons, then calculating the semivariance for (*m/2*) point pairs and finally taking its average. These stratum-averaged semivariances are then used to predict the sampling error $\hat{\hat{r}}$ for the entire sample by:

$$\hat{\hat{r}} = \sqrt{\sum_{h=1}^{L} \frac{W_h^2}{n_h} \cdot \bar{\gamma}_{A_h,A_h}} \qquad (2.)$$

where *L* is the number of strata, W_h is the relative area, n_h is the projected sample size and $\bar{\gamma}_{A_h,A_h}$ is the average semivariance between all pairs of possible sample points stratum *h*. Eq. 2 can also be seen as an approximation of the square root of the dispersion variance. This equation was used to obtain a relation between the total sample size *n* and the sampling error, by substituting values for n_h (assuming proportional allocation).

Since *PSC* depends on sampled depth, soils with deeper water tables (expressed by MHW) will have larger values of *PSC* compared to similar soils with shallower water tables. Recall, that sample B takes water-table classes as the primary strata for sampling (3.2). This would have a clear impact on the values of $\hat{\hat{r}}$. Therefore we redefined the quality criterion to:

$$VC = \frac{\hat{\hat{r}}}{\overline{PSC}} \qquad (3.)$$

Thus, a relation between *VC* and *n* was constructed for each primary stratum. As reference level for the *VC* we took the value obtained in the first sample, that of GWT III (*VC*=6.7%). The sample size of 6 primary GWT-units was obtained by comparing the above relations with this reference level. Sampling in GWT II and VI had already been planned during this analysis and was not adjusted, but the analysis for GWT II gave exactly the sample size that had been planned. Sampling in the non-GWT stratum could not be optimized via this approach since no a priori data ware available for these soils. The variograms for GWT II were assumed to be valid for GWT I since (i) no data were available for these soils as well, and (ii) MHW-values as well as land use are comparable between GWT I and II.

The obtained relations before sampling as well as the calculated values for *VC* after sampling are given in Figure 3 and Table 6. According to the experts' guess, *n*=1370 samples would have to be taken in sample B. The analysis of sample size indicated that *n*=1190 would be sufficient, a saving of more than 13% (k€ 290) of the total budget. This saving was 23% when related only to those samplings that had not yet been planned at the time of the analysis (1996): GWT I, IV, V and VII. The posterior calculation of the *VC* showed that only the sample in the primary stratum GWT I performed less in terms of VC, the other samples performed equal or better than predicted. Recall that no specific variogram was available for GWT I.

Figure 3 near here

3.4 Statistical Inference From Sample Data

3.4.1 Estimation from Sample A or from Sample B

The Stratified Simple Random design of Sample B was effectuated by selecting only one sample point from each delineation drawn in the first stage. Therefore, this design can be treated as a special case of the Stratified Two-Stage Random design of Sample A, and the same formulas can be used.

The spatial mean of a variable *z* in stratum *h* is estimated by:

$$\hat{\bar{z}}_h = \frac{1}{n_h} \sum_{i=1}^{n_h} \hat{\bar{z}}_{hi} \tag{4.}$$

with n_h = number of selected delineations in stratum *h* (2 in Sample A, 1 in Sample B), and $\hat{\bar{z}}_{hi}$ = mean of the sample values from delineation *i* in stratum *h* (4 values in Sample A; 1 value in Sample B). This estimator is *p*-unbiased, which means that if sampling and estimation were repeated many times then the mean of the estimates would equal the true mean.

The variance of the estimator is estimated by:

$$v(\hat{\bar{z}}_h) = \frac{1}{n_h(n_h - 1)} \sum_{i=1}^{n_h} (\hat{\bar{z}}_{hi} - \hat{\bar{z}}_h)^2 \tag{5.}$$

which for Sample A reduces to:

$$v(\hat{\bar{z}}_h) = \frac{1}{4}(\hat{\bar{z}}_{h1} - \hat{\bar{z}}_{h2})^2 \tag{6.}$$

The standard error of $\hat{\bar{z}}_h$ is estimated by $\sqrt{v(\hat{\bar{z}}_h)}$.

The mean of a group of *H* strata is estimated by:

$$\hat{\bar{z}} = \sum_{h=1}^{H} a_h \cdot \hat{\bar{z}}_h, \tag{7.}$$

a weighted mean of the stratum means, with weights a_h equal to the relative areas of the strata. The variance of the mean is estimated by:

$$v(\hat{\bar{z}}) = \sum_{h=1}^{H} a_h^2 \cdot v(\hat{\bar{z}}_h) \tag{8.}$$

and the standard error by $\sqrt{v(\hat{\bar{z}})}$. The two-sided 100(1-α)% confidence interval for $\bar{z}$ is given by:

$$\left[\hat{\bar{z}} - t_{\alpha,\nu} \cdot \sqrt{v(\hat{\bar{z}})}\ ;\quad \hat{\bar{z}} + t_{\alpha,\nu} \cdot \sqrt{v(\hat{\bar{z}})}\right] \tag{9.}$$

where v is the number of degrees of freedom:

$$\nu = \sum_{h=1}^{H} n_h - 1$$

The formulas for the mean are also used to estimate *fractions* of the area where a given condition is met, such as the fraction of the area where a quantitative variable exceeds a given threshold. Area fractions are estimated by first generating a 0/1 indicator variable from the sample data, with value 1 if the condition is met, and 0 otherwise. Then the above equations are applied to this indicator variable. By introducing a series of thresholds, and an indicator variable for each of them, the spatial cumulative distribution function of a quantitative variable can be estimated.

An estimate of a total, for instance a stock or a load of a substance, or the surface area within strata where a given condition is met, can be simply obtained by multiplying the estimated mean or fraction, respectively, with the total surface area of the strata. Similarly, the standard error of this estimated total or surface area can be obtained by multiplying the standard error of the mean or fraction with the total surface area of the strata.

An unbiased estimator of the spatial variance *$S^2(z)$* within a group of strata is:

$$\hat{S}^2(z) = Est(\overline{z^2}) - \hat{\bar{z}}^2 + v(\hat{\bar{z}}) \tag{10.}$$

where $Est(\overline{z^2})$ is the estimated mean of the target variable squared *(z^2)* (cf. de Gruijter et al. (2006), p.92) obtained in the same way as $\hat{\bar{z}}$, but using squared values.

Apart from groups of strata, interest is often in sub-areas that do not coincide with strata, but which can be defined in terms of properties recorded at the sample points. We refer to these sub-areas as domains of interest, or briefly 'domains'. An example application might be the estimation of the PSC of the soils under permanent pasture. The mean of a domain within a group of *H* strata is estimated by a ratio estimator as follows. We first define two ancillary variables *z'* and *x*, which equal *z* and 1, respectively, everywhere in the domain, but are zero elsewhere. The mean of the domain $\hat{\bar{z}}_D$ is then estimated as the ratio of the estimated means of *z'* and *x*:

$$\hat{\bar{z}}_D = \frac{Est(\bar{z}')}{\hat{\bar{x}}} = \frac{\sum_{h=1}^{H} a_h \cdot \sum_{i=1}^{n_h} \bar{z}'_{hi}}{\sum_{h=1}^{H} a_h \cdot \sum_{i=1}^{n_h} \bar{x}_{hi}} \tag{11.}$$

where $\hat{\bar{z}}'_{hi}$ and $\bar{x}_{hi}$ are the sample means of *z'* and *x*, respectively, in delineation *i* of stratum *h*; $\hat{\bar{x}}$ is the estimated area fraction of the domain. The sampling variance of $\hat{\bar{z}}_D$ is estimated by (Cochran, 1977):

$$v(\hat{z}_D) = \frac{1}{\bar{x}^2} \cdot \sum_{h=1}^{H} \frac{a_h^2}{n_h(n_h - 1)} \cdot \sum_{i=1}^{n_h} \left(\bar{d}_{hi} - \frac{1}{n_h} \cdot \sum_{i=1}^{n_h} \bar{d}_{hi} \right)^2 \tag{12.}$$

where $\bar{d}_{hi}$ is the sample mean of $d = z' - \hat{\bar{z}}_D \cdot x$ in delineation *i* of stratum *h*. If the true value of the area fraction of the domain ($\bar{x}$) is not known from the map, then the estimate $\hat{\bar{x}}$ is used instead.

Fractions, spatial cumulative distribution functions, totals and surface areas within domains are estimated in the same way as for strata. Also the spatial variance $S_D^2(z)$ is estimated similarly:

$$Est(S_D^2(z)) = Est(\overline{z_D^2}) - \hat{\bar{z}}_D^2 - v(\hat{\bar{z}}_D) \tag{13.}$$

where again $Est(\overline{z_D^2})$ is the estimated mean of the target variable squared (z^2) obtained in the same way as $\hat{\bar{z}}_D$, but using squared values.

3.4.2 Estimation from both samples

The target area of Sample A is a sub-set of the target area of Sample B; in that sense these samples are overlapping. For estimates in strata or domains outside the Sample A area, obviously only the Sample B data can be used. However, for strata or domains containing sample points from both samples, a combined estimate of a mean or fraction is calculated as the average of two estimates from the samples separately, weighted with the inverse of their variance:

$$\hat{\hat{z}} = \frac{\frac{1}{v(\hat{\hat{z}}_A)}}{\frac{1}{v(\hat{\hat{z}}_A)}+\frac{1}{v(\hat{\hat{z}}_B)}}\hat{\hat{z}}_A + \frac{\frac{1}{v(\hat{\hat{z}}_B)}}{\frac{1}{v(\hat{\hat{z}}_A)}+\frac{1}{v(\hat{\hat{z}}_B)}}\hat{\hat{z}}_B = \frac{v(\hat{\hat{z}}_B).\hat{\hat{z}}_A+v(\hat{\hat{z}}_A).\hat{\hat{z}}_B}{v(\hat{\hat{z}}_A)+v(\hat{\hat{z}}_B)} \qquad (14.)$$

with sampling variance:

$$v(\hat{\hat{z}}) = \frac{v(\hat{\hat{z}}_A)\cdot v(\hat{\hat{z}}_B)}{v(\hat{\hat{z}}_A)+v(\hat{\hat{z}}_B)} \qquad (15.)$$

4. DATA AND INFORMATION SYSTEM

A computerized soil information system for storage, retrieval and statistical processing of the sample data was created. This system comprises an Oracle™ data base with detailed profile descriptions at 2,524 sample points (for locations sample B see Figure 2) and analytical data for 5,764 soil layers. GENSTAT™ routines were linked to the data base for statistical processing described in sections 3.4.1-3. Nearly all soil samples were sieved, dried and stored for future analysis. Table 5 gives an overview of the measured properties and the number of locations and strata.

5. APPLICATION EXAMPLES

5.1 Phosphate saturation

In 2000, the Proportion of Phosphate saturation of Dutch soils was estimated on request of the Dutch Ministry of Agriculture as part of the annual review of the manure policy. When 25% of the PSC is occupied by Phosphate, the soil is considered Phosphate saturated. Sample B was used to make this assessment, and it came out that the average PSP in sandy soils under agriculture was 30.1%. The advantage of the statistical sampling approach, besides its unbiasedness, was that a more detailed analysis could be done as well. Figure 4 illustrates that a distribution of the area exceeding different threshold values for PSP can easily be made. It is apparent, that more than one third of the area of sandy soils under agricultural land use is only slightly above the 25% threshold. This means that a minor reduction in adsorbed Phosphate may have a clear impact on the area with Phosphate saturation.

Figure 4 near here

5.2 Parameterization, calibration and verification of STONE

STONE is a chain model to study and predict the magnitude of the ground- and surface water pollution with N and P for a range of environmental conditions. STONE operates at the full extent of the Netherlands, and is routinely being used in the environmental outlook and the state of the environment. For the parameterization of the 6405 plots of the soil submodel, the data of Sample B were essential (Kroon et al., 2001). Phosphate, MHW and MLW data were used for model verification at different scales (Overbeek et al., 2001; Leopold et al., 2006).

5.3 Characterization of nature areas

At the request of the Netherlands Environmental Assessment Agency a statistical characterization was made of selected soil characteristics in nature areas. As domain of interest we took all sample points where the land use “nature” was recorded, and selected the data pH-KCl, %OM, $CaCO_3$, Al-ox, Fe-ox, P-ox, CEC and cations Al, Ca, Fe, K, Mg, Mn, Na) at depths of 1, 15, 30 and 45 cm depth. Subsequently, average values and standard errors were calculated for domains within spatial entities (nature areas within defined groups of soil map-units based on soil texture class) within the primary GWT-strata. These data now serve as reference data for environmental outlooks.

5.4 Estimation of the carbon stock

The common reporting format for C stocks on specific land uses (article 5.2 of the Kyoto Protocol) requires national submissions of these data. In order to make an assessment for the Netherlands (Kuikman et al., 2003), sample B data were used to calculate the total C stock in the top layer (0-30 cm) of Dutch soils. This was found to be 286 Tg C, with a 95% confidence region 280-293 Tg C. Additionally, the C stock in the organic soils in the layer between 30 and 120 cm depth was calculated, which adds another 142 Tg C to the stock. A subdivision to different kinds of land use could be made as well.

6. DISCUSSION

6.1 On the sampling methods

The sampling density was optimized for upgrading groups of soil map units, but is far too low to upgrade individual map units. An additional sampling program would be needed. The data that have now become available would be instrumental to optimize such new sampling effort, e.g. by analyzing the sampling error of Eq. 12 for samplings in regional or thematic domains.

The usage potential of the NSSP-data for mapping soil parameters like PSP has not been investigated but sampling density is probably too low to map with high accuracy at presentation scales near 1:50,000.

6.2 On the rationale and cost-efficiency

Referring to the purposes 1 and 3 in section 2.1, there seems to be an inconsistency in the soil sampling program. On the one hand, the map layer with water table depth classes is updated, on the other hand, the original water table class map is used for clustering soil map units in the upgrading projects. This approach was enforced by the following facts (i) both projects were expected to extend over several years, (ii) a continuation of the funding for the upgrading project would be highly uncertain if it would be paused until completion of the remapping program, (iii) the planning of the remapping program was uncertain because of the large number of stakeholders and funding agencies involved. Two important consequences of this choice might be (i) a potentially less efficient stratification by GWT-class since this map layer still had to be updated at this time, and (ii) a potentially worse quality of predictions using the old soil-GWT map with upgraded data. The second consequence will be of importance for nation-wide predictions using the updated GWT map, and may also affect the quality of estimates in domains, strata or delimited geographical regions. Now that updated GWT-class maps are becoming available (Finke et al., 2004), poststratification techniques (e.g., Deville et al., 1993) can be used to improve estimates by adjusting sample weights. To assess the predictive power of the stratification by GWT-class for both the old soil-GWT maps and the updated maps, we performed 2 analyses of variance (Table 7). The GWT taken from the original map at each of the sampling sites explained 12.7% of the variance of PSC, and this value increased to 26.4% with the GWT at the same locations on the updated map. These results indicate (i) that the assumption that GWT would be a useful stratifier for PSC was positively verified, and (ii) that poststratification using the updated GWT-map will probably increase the quality of estimates.

The a priori analysis of sample size, using the old GWT-map and available PSC-data allowed for a reduction in sampling cost of 13% of the budget estimate based on expert judgement only, while reaching set quality levels (section 3.3). It is possible that a further reduction in sampling cost could have been reached when the analysis described in section 3.3 would have been done after a GWT map update. We did not analyze this possible saving, but considering the fact that the cost of the map update were reduced because substantial numbers of GWT-data were available from the upgrading projects, we think the net effect would be minor.

6.3 On future use and expansion of the data

Since aliquots of the soil samples were retained, additional sampling for other soil variables is possible. In case these new variables are correlated to measured variables, smaller sample sizes will allow for estimates of good quality. Ratio or regression estimators (Cochran, 1977) make use of the relationships between 2 soil variables of which one is measured to calculate standard errors for the newly sampled as a function of sample size.

The current NSSP data base may serve as a starting point for a national scale monitoring program, e.g. for monitoring Carbon Stocks and PSP. Recently, de Gruijter et al. (2006) presented an extensive overview of design-based and model-based sampling designs and inference for the estimation of global quantities in space and time. Examples of these quantities are the change in spatial mean and the temporal trend in the spatial mean, possibly in circumstances of intervention, and the frequency and duration of events like exceedance of threshold values. NSSP allows for the implementation of static, dynamic, rotational and BACI (Before-After-Control-Impact) design based approaches. In case the temporal domain is to be monitored following a model-based approach, NSSP can be used as well using techniques like space-time kriging or simulation for inference.

Future use of NSSP, especially in the monitoring context, will ask for research on the employment of prior information and on the optimization of sample selection (de Gruijter et al., 2006).

7. CONCLUSIONS

The NSSP was defined as a framework of interrelated projects to answer to prioritized data needs of soil data users in The Netherlands. Due to the variety of wishes, three groups of projects (map upgrading, map updating and PTF-upgrading) had to be defined. In each one group, the sampling design, performance criteria and optimal sample size were defined. This paper focuses on the map upgrading projects. A prior analysis of a performance criterion related to the sampling error resulted in a cost saving of 13% relative to total cost determined by expert judgement. Posterior analysis showed that the quality criterion was reached or better in 6 out of 7 cases. The NSSP is already showing its usage potential for various kinds of environmental studies and could be a sound basis for future national scale monitoring programs. In conclusion, given the constraints and the complex funding of the subprojects, we consider NSSP a reasonable success.

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Tables

Table 1. Meta-priorities for soil data collection derived from interviews with users. Scores (scale 0-100) are the product of the usage intensity and the urgency of the wishes. ~~Indicated~~ priorities were omitted from the data collection program due to budget constraints.

Meta-priority	Score
Improved quality of physical data	14,4
Improved currency of present water table data	13,7
~~New types of soil physical data~~	8,7
~~Improved spatio-temporal presentation of soil physical data~~	6,1
Improved detail (scale) of soil maps [*]	5,2
Improved spatio-temporal presentation of water table data	4,7
~~Improved data on temporal variability of soil chemical data~~	3,9
~~Improved spatio-temporal presentation of soil chemical data~~	3,9
New types of soil chemical data	3,9
Improved currency of soil chemical point data	3,2
Improved data on temporal variation of water tables	2,7
Improved pedotransfer functions for soil chemical data [*]	2,5
Improved quality of soil chemical point data	0,3

[*] in commissioned projects

Table 2. General wishes from soil data users. Scores are percentages of the 35 interviewed persons.

General wish	Specification	Users (%)
Presentation	Standardization and documentation of applied methods	31
Quality	Statistical confidence measures	26

Table 3. Some operational statistics of the sampling projects.

Project no.	Cluster of map units defined as:	Period	Area (km^2)	Number of Points	Number of Samples
1	*Typic Haplaquods*	1988-1990	1,732	520	0
2	*Typic Humaquepts*	1989-1990	763	608	0
3	Water table class I	1998-1999	190	115	307
4	Water table class II	1994-1996	3,299	200	796
5	Water table class III	1993-1995	4,532	180	895
6	Water table class IV	1999-2000	1,518	132	451
7	Water table class V	1996-1998	5,322	200	939
8	Water table class VI	1996-1998	7,225	210	1019
9	Water table class VII	1998-1999	5,381	156	675
10	Water table class assoc.	2000-2001	1,176	143	458
11	No water table class	2000-2001	441	60	224
Program	*All map units*	*1988-2001*	*29,084*	*2,524*	*5,764*

Table 4. Some design statistics of the sampling projects .

Project no.	**Cluster of map units defined as:**	**Number of**		**Points per**	
		strata	**points**	**stratum**	**100 km^2**
1	*Typic Haplaquods*	65	520	8.0	30.0
2	*Typic Humaquepts*	66	608	9.2	79.9
3	Water table class I	5	115	23.0	60.5
4	Water table class II	9	200	22.2	6.1
5	Water table class III	6	180	30.0	4.0
6	Water table class IV	7	132	18.9	8.7
7	Water table class V	21	200	9.5	3.8
8	Water table class VI	17	210	12.4	2.9
9	Water table class VII	18	156	8.7	2.9
10	Water table class assoc.	9	143	15.9	12.2
11	No water table class	3	60	20.0	13.6
Program	*All map units*		*2,524*		*8*

Table 5. Sampled soil characteristics.

Characteristic	A		Sample B (Water Table Class)													
	T.Humaquepts	***T.Haplaquods***	**I**		**II**		**III**	**IV**		**V**		**VI**		**VII / VII***	**Assoc.**	**-**
	4 samples in 12 map units	2 samples in 2 map units	4 Strata	1 Stratum	8 Strata	1 Stratum	6 Strata	6 Strata	1 Stratum	20 Strata	1 Stratum	16 Strata	1 Stratum	18 Strata	9 Samples	3 samples, in soils without GWT-class
	Agriculture + nature	Agriculture + nature	agriculture	nature	agriculture	nature	Agriculture + nature	agriculture	nature	agriculture	nature	agriculture	nature	agriculture	Agriculture + nature	Agriculture + nature
Site information																
X, Y, horizon depths	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Field classification code	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Land use	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Geological formation	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Rootable depth	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Physical characteristics (estimates)																
Humus%	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Clay, silt, M50 sand fraction	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Ground water																
MHW, MLW, GWT-class	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
Chemical characteristics (solid phase)																
pH-KCl			■	■	■	■	■	■	■	■	■	■	■	■	■	■
$CaCO_3$			■	■	■	■	■	■	■	■	■	■	■	■	■	■
Org. Matter			■	■	■	■	■	■	■	■	■	■	■	■	■	■
Pw-number			▨		▨		▨ ag	▨		▨		▨		▨ ag	▨	■
Pal			▨		▨		▨ ag	▨		▨		▨		▨ ag	▨	■
P-ox	■ 528		■	■	■	■	■	■	■	■	■	■	■	■	■	■
Al-ox	■ 528		■	■	■	■	■	■	■	■	■	■	■	■	■	■
Fe-ox	■ 528		■	■	■	■	■	■	■	■	■	■	■	■	■	■
CEC				▨		▨	▨ nt		▨		▨		▨	▨ nt		■
Exch. Al, Ca, Mg, Na				▨		▨	▨ nt		▨		▨		▨	▨ nt		■
Mineral N						▨	▨									■
Total N					▨		▨									■
C elem.						▨	▨									■
P_2O_5 without oxidation					▨		▨									■
P_2O_5 with oxidation					▨		▨									■
Chemical characteristics (soil solution)																
P-tot.							■									
P ortho							■									
Chemical characteristics (ground water)																
H, Ca, Mg, K, Na, Cl, SO_4, HCO_3^-							░									
EC							░									
pH							░									

ag=agricultural areas only; nt=natural areas only; 528=at 528 locations

Analysed samples from:

All horizons	Topsoil horizons only	At MHW-level	Not analyzed
■	▨	░	□

Table 6. Descriptive statistics, variogram parameters and sample sizes for Phosphate Sorption Capacity (PSC), by primary stratum and based on available information before the start of NSSP.

GWT	I	II	III	IV	V	VI	VII
Descriptive statistics							
N (profiles)	0	99	219	59	189	279	223
Mean PSC *	-	10 124	13 028	16 496	10 003	20 914	58 765
Median PSC *	-	8 544	9 504	14 265	9 337	20 214	48 292
Minimum PSC *	-	838	604	2 212	560	4 677	6 422
Maximum PSC *	-	46 651	84 842	53 971	70 754	58 778	225 281
sd	-	7 893	11 652	1 056	6 659	7 999	39 068
se	-	793	787	1 376	484	479	2 616
VC (%)	-	78%	89%	64%	67%	38%	66%
Semi-variogram							
model	-	EXP #	EXP #	SPH #	EXP #	SPH #	SPH #
Nugget (PSC^2)	-	26.5 10^6	96.6 10^6	77.0 10^6	15.4 10^6	36.9 10^6	94.7 10^7
Sill (PSC^2)	-	71.5 10^6	209.6 10^6	87.2 10^6	55.9 10^6	45.7 10^6	206.7 10^7
Range (m)	-	42.50 10^3	25.60 10^3	4.25 10^3	33.30 10^3	4.28 10^3	7.12 10^3
SSD/SST fitted model ($1-R^2$)	-	0.548	0.322	0.630	0.526	0.420	0.305
Classes in empirical variogram	-	8 x 10 km	20 x 3 km	4 x 2 km	20 x3 km	6 x2 km	8x1.5km
Sample size							
Expert guess of N	200	200	180	200	200	210	180
Decision after analysis	115	200&	180&	129	200	210&	156
Posterior value of *VC* $	8.4	5.5	(6.7)	7.1	4.6	3.8	3.5

* PSC in kg P_2O_5 per ha

\# EXP=Exponential model; SPH=Spherical model

& Samplings within GWT II and GWT VI strata were already in execution during the analysis

$ Expected value of *VC* according to design criterion of GWT III stratum: 6.7%

Table 7. Analyses of variance of PSC versus original GWT and updated GWT.

Original GWT	**df**	**SS**	**MS**	**F**	**%Var.Expl.**
Between GWT-classes	6	3.65186E+10	6.08643E+09		
Within -GWT-classes	1190	2.50091E+11	2.10160E+08		
Total	1196	2.86609E+11	2.39640E+08	28.96	12.7

Updated GWT	**df**	**SS**	**MS**	**F**	**%Var.Expl.**
Between GWT-classes	6	7.50210E+10	1.25035E+10		
Within -GWT-classes	1183	2.08814E+11	1.76512E+08		
Total	1189	2.83835E+11	2.38717E+08	70.84	26.4

List of Figures

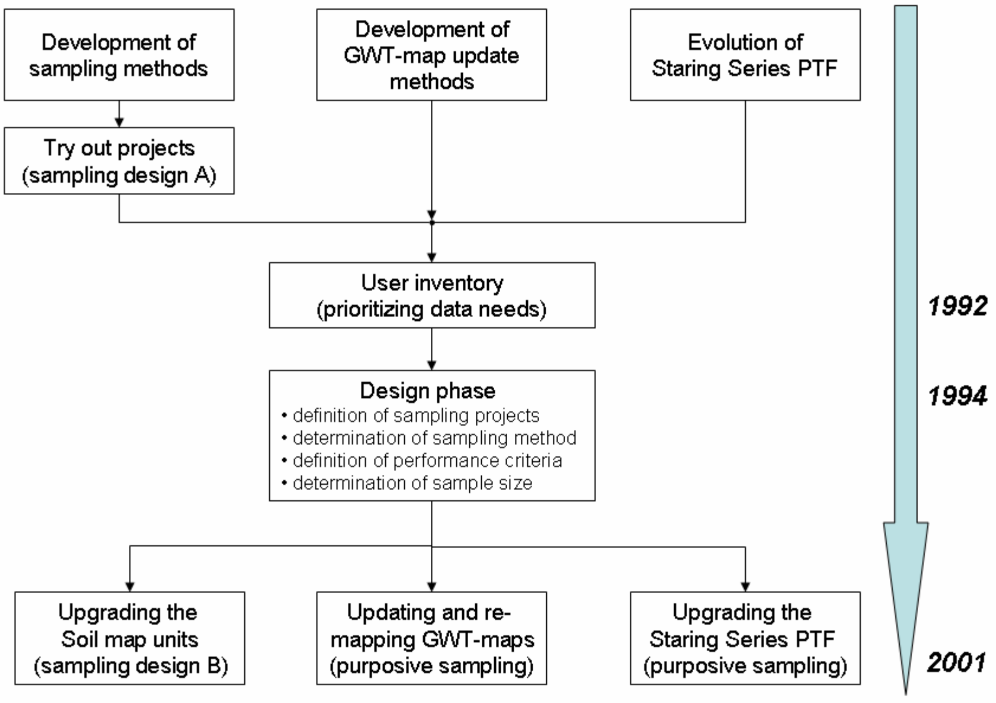
Development of sampling methods
Development of GWT-map update methods
Evolution of Staring Series PTF
Try out projects (sampling design A)
User inventory (prioritizing data needs)
1992
Design phase
• definition of sampling projects
• determination of sampling method
• definition of performance criteria
• determination of sample size
1994
Upgrading the Soil map units (sampling design B)
Updating and re-mapping GWT-maps (purposive sampling)
Upgrading the Staring Series PTF (purposive sampling)
2001

Fig. 1

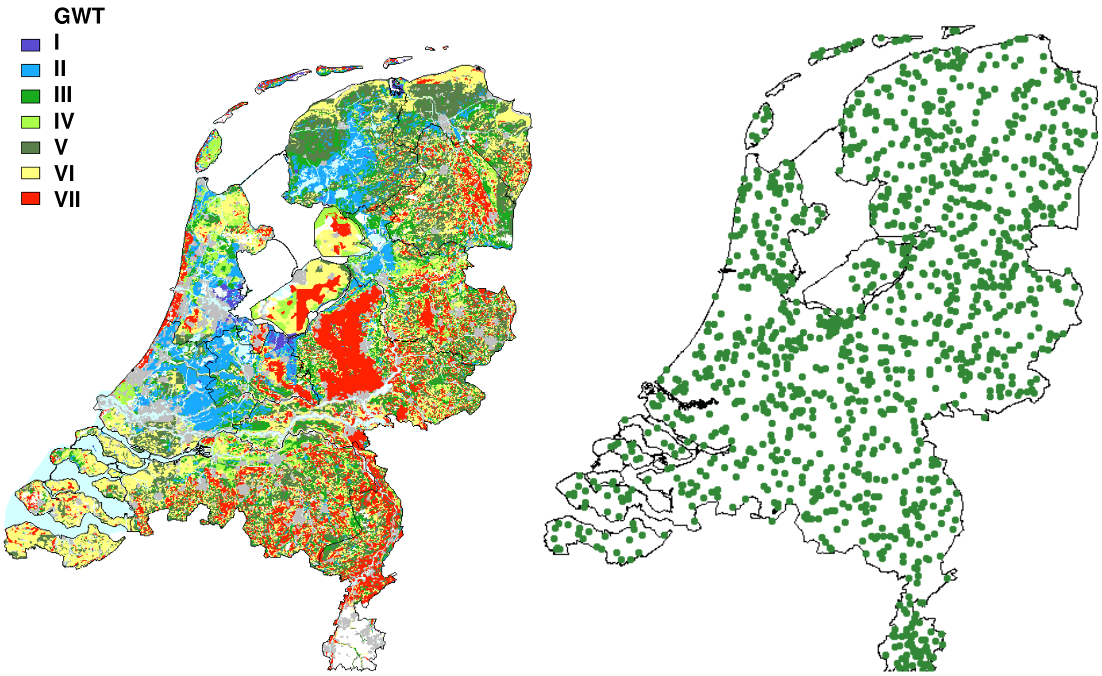

Fig. 2

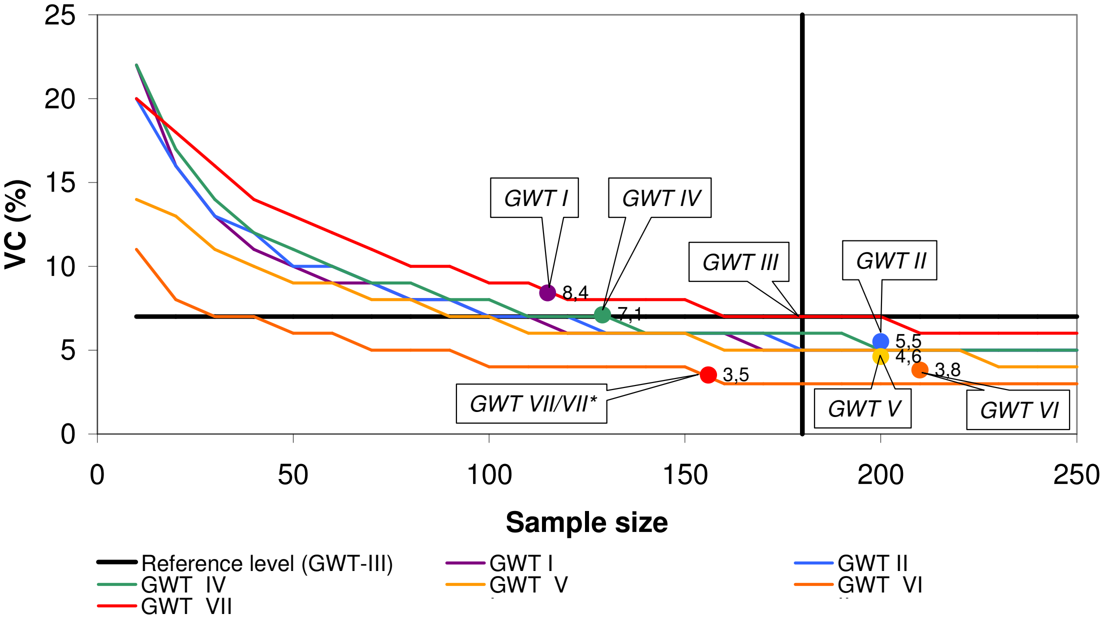
25
20
15
10
5
0
VC (%)
0
50
100
150
200
250
Sample size
GWT I
GWT IV
GWT III
GWT II
8,4
7,1
5,5
4,6
3,8
3,5
GWT VII/VII*
GWT V
GWT VI
Reference level (GWT-III)
GWT I
GWT II
GWT IV
GWT V
GWT VI
GWT VII

Fig. 3

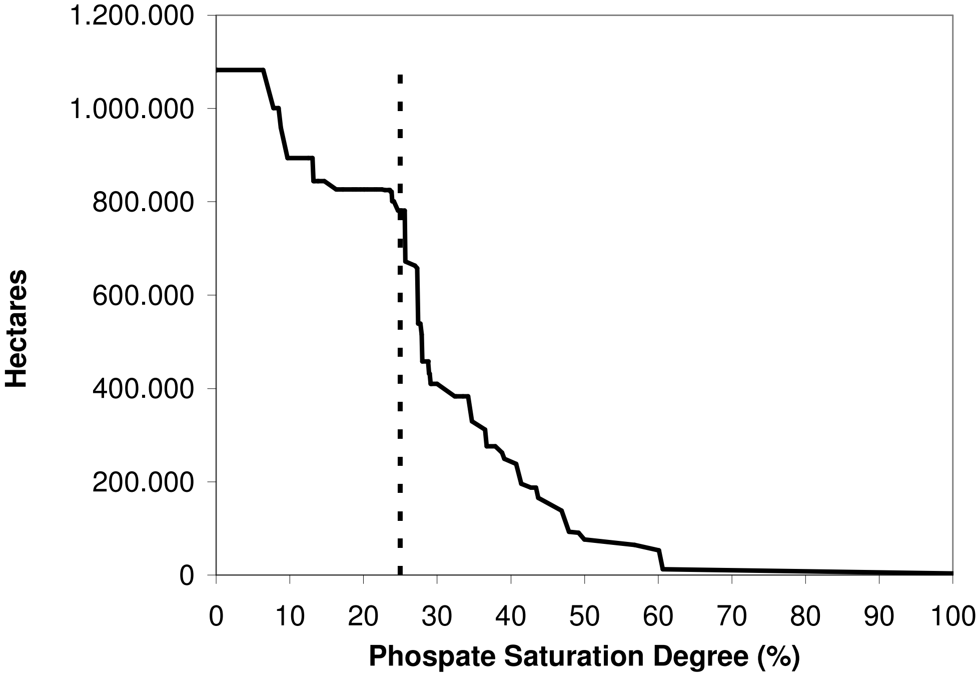
1.200.000
1.000.000
800.000
600.000
400.000
200.000
0
Hectares
0
10
20
30
40
50
60
70
80
90
100
Phospate Saturation Degree (%)

Fig. 4