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Generating spatially and statistically representative maps of environmental variables to test the efficiency of alternative sampling protocols

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ABSTRACT

Accurate assessment of environmental variables is vital to understanding the global issues of land-use change and climate change, but is hindered by their high spatial and temporal heterogeneity. Extensive surveys are needed to model such large-scale problems, with their success dependent on adequate sampling protocols. We present a robust method for designing efficient sampling protocols for environmental variables. The SIMAP method involves the following steps: 1) Selecting sites that cover a representative range of spatial variability, 2) Intensive and spatially-accurate surveys within sites, 3) construction of continuous Maps that replicate the spatial and statistical variation of the surveys, 4) Accuracy simulations based on sampling of these maps and 5) determining a sampling Protocol for subsequent broader surveys. To illustrate the method, we used estimation of soil C stocks in mixed-species tree plantings and pastures to estimate carbon sequestration following reforestation. Soil C was surveyed intensively from these two land uses at several farms that covered a large rainfall gradient to provide contrasting datasets. In this example, sampling simulations showed that a systematic design generally required one less sample than a restricted-random design to achieve the same accuracy, while a simple-random design required substantially more samples. We found taking a minimum of 30 soil samples was needed for both bulk density and C concentration to accurately estimate soil C content within a 1-ha plot in a pasture or tree planting, which suggests many previous surveys of soil C were sampled inadequately. The SIMAP method could be readily applied to a range of abiotic and biotic variables, with the construction of maps allowing most sampling intensities and designs to be tested. Adequate sampling intensities differ widely among environmental variables, so the SIMAP method enables researchers to determine which variables require more investment. For many variables, costs may be minimised while maintaining a high accuracy of the sampling design via bulking of well-mixed samples prior to analysis.

1. Introduction

For many environmental variables, designing efficient and robust sampling protocols (i.e. balancing the need for sufficient sites to be representative, but with also adequate sampling within a sites) is crucial for providing accurate information at scales appropriate to understanding land-use change and climate change. However, most environmental variables exhibit a high degree of spatial and temporal heterogeneity, presenting a significant challenge to their accurate measurement (Vasseur and McCann, 2007).

Environmental variables change spatially with topography, geology and climate, and temporally with the seasons, development and disturbance. To ensure adequate spatial sampling of biological processes, several designs have been used (De Gruijter et al., 2006). Without prior knowledge of a system, ecologists typically use *simple-random* or *systematic* (i.e. based on a regular grid) sampling. When the spatial pattern of potential predictors is known, samples can be taken randomly within strata of the predictor using a *stratified random* design. In the absence of such knowledge, a *restricted-random* design can be used by randomly sampling within cells of a regular grid (De Gruijter

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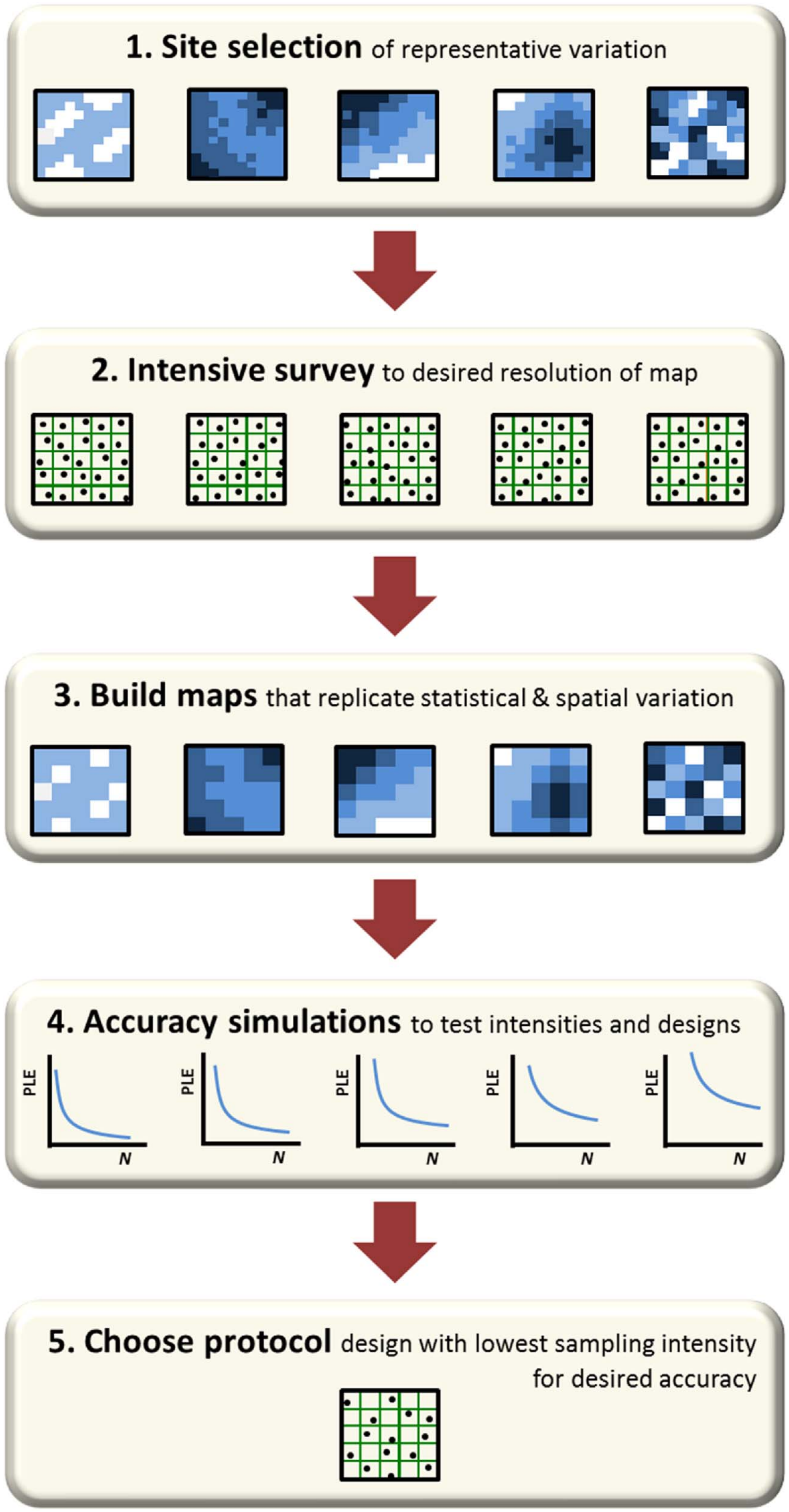

Fig. 1. Steps involved in the SIMAP method (Site selection, Intensive surveys, Map build, Accuracy simulations and Protocol choice) for determining sampling protocols. Five areas are presented with increasing spatial variability from left to right. PLE = probable limit of error.

et al., 2006). Samples that are representative of the variation and spatially balanced can be collected with more complex designs, such as generalised random tessellation stratified sampling (Stevens and Olsen, 2004).

Sampling requirements for statistical accuracy often are not determined prior to the main survey or from the resultant data set (Caughlan and Oakley, 2001). An understanding of variability in an environmental variable is necessary to statistically guide the required sampling intensity based on either choosing a target variance (e.g. 80% chance of being within 10% of the population mean, (Vasconcelos et al., 2014),

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