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Research article

Exploring effective sampling design for monitoring soil organic carbon in degraded Tibetan grasslands

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A B S T R A C T

The effects of climate change and human activities on grassland degradation and soil carbon stocks have become a focus of both research and policy. However, lack of research on appropriate sampling design prevents accurate assessment of soil carbon stocks and stock changes at community and regional scales. Here, we conducted an intensive survey with 1196 sampling sites over an area of 190 km^2 of degraded alpine meadow. Compared to lightly degraded meadow, soil organic carbon (SOC) stocks in moderately, heavily and extremely degraded meadow were reduced by 11.0%, 13.5% and 17.9%, respectively. Our field survey sampling design was overly intensive to estimate SOC status with a tolerable uncertainty of 10%. Power analysis showed that the optimal sampling density to achieve the desired accuracy would be 2, 3, 5 and 7 sites per 10 km^2 for lightly, moderately, heavily and extremely degraded meadows, respectively. If a subsequent paired sampling design with the optimum sample size were performed, assuming stock change rates predicted by experimental and modeling results, we estimate that about 5–10 years would be necessary to detect expected trends in SOC in the top 20 cm soil layer. Our results highlight the utility of conducting preliminary surveys to estimate the appropriate sampling density and avoid wasting resources due to over-sampling, and to estimate the sampling interval required to detect an expected sequestration rate. Future studies will be needed to evaluate spatial and temporal patterns of SOC variability.

1. Introduction

Monitoring natural resources over space and time is expected to promote a better understanding of ecosystem processes, and to provide information to inform decision making for resource protection and management (Lark, 2009). Soil organic carbon (SOC) is of particular importance in building soil fertility for sustainable development and in reducing atmospheric CO_2 concentration through carbon (C) sequestration (Lal, 2004). However, due to typically large spatial and small temporal variability relative to SOC stocks, efficient estimation of SOC stocks and their change remains a challenge in monitoring programs (Allen et al., 2010). Research can inform the design of cost-effective sampling schemes to achieve monitoring objectives.

Generally, sampling schemes are based on one of two

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contrasting philosophies of statistical investigation: the design- and the model-based approach (Allen et al., 2010; de Gruijter et al., 2006). The essential difference between the two approaches is whether locations are chosen at random or purposively (Brus and de Gruijter, 2012; de Gruijter et al., 2006). Studies estimating the global or regional mean status of SOC stocks often select design-based sampling, as fewer observations and fewer strong assumptions are required (Brus and de Gruijter, 2012; Lark, 2009). For estimating the mean C stock and monitoring its change, sampling design must consider both space and time dimensions (Brus and de Gruijter, 2011). de Gruijter et al. (2006) distinguished and evaluated several types of space-time designs for monitoring regional trends. None of these designs scored best on both status and trend measures (Allen et al., 2010; Brus and de Gruijter, 2013). The applicability of these designs depends on the aim of soil monitoring. Heim et al. (2009) demonstrated that stratified sampling of parent materials reduced the error of SOC estimates in a forest site. Theoretical considerations and empirical studies indicate that a paired sampling scheme is likely to be the most efficient for estimating change in a soil variable (Heim et al., 2009; Lark, 2009).

The Tibetan plateau is a large C reservoir (Yang et al., 2008). Significant warming and anthropogenic disturbance due to overgrazing have led to widespread grassland degradation on the plateau in the past five decades, which has caused rapid C loss (Chen et al., 2013). On the other hand, ecological restoration programs can significantly promote grassland recovery and increase C sequestration (Wang et al., 2011). Policy makers and environmental managers have a pressing need for detailed information about the status of and change in SOC stocks on the plateau. Unfortunately, existing SOC inventories are characterized by large uncertainties that stem from insufficient sample size or lack of a suitable sampling design (Chang et al., 2014a; Yang et al., 2008).

In this study, we conducted an intensive sampling campaign in two communities on the eastern Tibetan plateau. We investigated the variability of SOC in grasslands at different levels of degradation. Our objectives were to: (1) estimate the optimum sample size to meet a desired SOC stock estimate with an uncertainty of 10%, and (2) estimate the minimum detectable change in C stock with the optimum sample size. We then predicted the time interval between soil inventories for detecting a specific sequestration rate with the desired statistical confidence (95%) and power (0.80). On the basis of this analysis, we recommend a sampling framework for estimating the status of and trend in SOC stocks on the community scale.

2. Materials and methods

2.1. Study area

The study area is located in Tangde and Xiala villages in Zeku County, Qinghai province, China (Fig. 1). It covers roughly 190 km^2, with elevations ranging between 3400 and 4100 m above sea level. The site is characterized by a continental plateau climate. The mean annual temperature is −2 to 2.3 °C and mean annual precipitation is 460 mm. Under-developed gravel soils are relatively uniform, which are classified as Typic Cryoboroll in the US soil taxonomy. Alpine meadow occupies over 90% of the study area, which is dominated by *Kobresia pygmaea*, *Kobresia humilis* and *Kobresia tibetica*. Grassland degradation has taken place across the study area due to overgrazing in past decades. Degraded alpine meadows have native vegetation coverage of less than 85%, and can be further characterized as lightly degraded (70–85% cover), moderately degraded (50–70% cover), heavily degraded (30–50% cover) or extremely degraded (<30% cover) (Ma et al., 2002). According to an unpublished vegetation survey, lightly, moderately, heavily and extremely degraded grasslands account for 41.6, 31.4, 13.5 and 13.5% of the study area, respectively.

2.2. Field sampling and analysis

Our intensive sampling survey was stratified by degradation status. A total of 1196 sites were sampled between August–September 2009 and 2010, with 591, 204, 121 and 280 sampling sites for lightly, moderately, heavily and extremely degraded grasslands, respectively. At each site, five 20 cm deep soil cores were taken within a 25 m^2 sampling plot and bulked to form a composite soil sample. Bulk density was sampled with a 100 cm^3 (5.04 cm in diameter) metal core. When rock fragments prevented the insertion of the core in soil, another position within the sampling plot was chosen. Aboveground biomass at each site was measured by clipping in one 0.25 m^2 quadrat located at the center of each sampling plot. One soil core (8 cm in diameter) was sampled to determine root biomass. Root samples were then carefully washed through a 0.25 mm mesh sieve. All plant tissue was dried at 60 °C until a constant mass was achieved.

Composite soil samples were air-dried, sieved (2 mm mesh), handpicked to remove fine roots, and then ground in a ball mill. SOC concentration was determined by dry combustion analysis with a Shimadzu carbon analyzer (TOC-5000, Shimadzu Corp., Kyoto, Japan). Soil texture was determined by a particle size analyzer (MasterSizer, 2000) after removal of organic matter and calcium carbonates. Samples for bulk density determination were dried at 105 °C for 48 h, and passed through a 2 mm sieve to obtain the fine earth fraction. Soil rock content was measured by dry sieving the stones and measuring the dry weights of stones. For each site, SOC density was determined as the product of SOC concentration, bulk density, and sampling depth, and corrected for rock fragments.

2.3. Statistical analysis

The distribution of SOC densities was tested for normality by the Kolmogorov-Smirnov test. One-way ANOVA was used to compare soil and plant variables of different degradation strata using SPSS version 16.0 (SPSS Inc. Chicago, Illinois, USA). To explore the role of elevation, we additionally analyzed SOC in relation to elevation.

2.3.1. Statistical power for SOC stock estimates

We evaluated the efficacy of the current sampling scheme, i.e. whether the number of sampling sites was sufficient or not. Previous studies have presented detailed descriptions of procedures for power analysis (Allen et al., 2010; Kravchenko and Robertson, 2011). Here we summarize the key points relevant to the power analysis conducted in this study. First, we calculated the individual mean and variance for each degradation stratum. Then, we set a tolerable uncertainty of 10% above and below the sample mean. Once those parameters are specified, the probability (statistical power) to detect a deviation greater than the tolerable uncertainty with 95% confidence (using a two-tailed test) can be calculated for different sample sizes. In our experience, the mean and variance of the light degradation (591 samples) were $\mu = 9.75$ kg C m^{-2} and $s^2 = 1.32$ (kg C $m^{-2})^2$, respectively. A significant deviation lies outside the interval $\mu \pm 1.96\ s$, which corresponds to $\mu < 7.50$ and $\mu > 12.01$. The mean at the limit of tolerance was $\mu + 0.1\mu = 10.73$. For $\mu = 12.01$ the normal deviate is $z_u = (12.01–10.73)/s = 1.11$. For $\mu = 7.50$ the normal deviate is $z_l = (7.50–10.73)/s = -2.81$. The probability associated with these deviates are $P(z_l) < zl \approx 0$ and $P(z_u) > z_u = 0.999$. These quantities are summed to yield the statistical power to detect a deviation greater than the tolerable uncertainty with 95% confidence (two-tailed test). Power analysis