# Long-term monitoring strategies for ecological reclamation programmes using spatially balanced rotating panel designs

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## Abstract

1. Environmental monitoring programmes associated with ecological reclamation are critical to various stakeholder groups and important for regulatory compliance, to assess site performance, and to inform decision management. As logistical constraints are common, strategies for sampling multiple locations or large areas over time are likely to improve monitoring programmes. Rotating panel designs can be used to conduct statistically valid field sampling across spatial and temporal schedules, resulting in significant time- and cost-savings without sacrificing quality of monitoring data. Spatially balanced sampling designs have also been useful for monitoring natural resources as they ensure good coverage over an area of interest.
2. We propose using a spatially balanced rotating panel sampling design which utilizes neighbourhoods created by spatial and auxiliary information. As it is common for reclamation efforts across space to be influenced by environmental factors, we assume nearby locations which are treated with the same inputs will be more similar to each other than far away areas. We use a one-point-per-cluster sampling design to ensure good spatial coverage of the large area.
3. This approach is helpful because it guarantees local coverage during each sampling phase, achieves equal inclusion probabilities, and has excellent spatial spread. We give examples from the Pinedale Anticline natural gas field in Sublette County, Wyoming, USA. Our examples include a natural gas well pad reclamation programme consisting of 303 locations as well as a ~21 km pipeline right-of-way system undergoing reclamation.
4. As ecological reclamation will be continuously relied upon to mitigate land surface disturbance and combat environmental threats such as biodiversity loss and climate change, sound long-term monitoring programmes to document outcomes are critical.

**Keywords:** ecological reclamation, ecological restoration, environmental monitoring, environmental sampling, spatially balanced sampling

## 1 | INTRODUCTION

Ecological reclamation is necessary to ensure ecosystem disturbances are not permanent and are critical to meeting ambitious environmental goals related to climate change, biodiversity decline, ecosystem integrity and for social and economic reasons (Harris, Hobbs, Higgs, & Aronson 2006; Shackelford et al. 2013; Suding et al. 2015; Brondizio et al. 2019). Terrestrial land surface disturbance is caused by a variety of factors including fires, drought, natural resource extraction, and other anthropogenic development (Shackelford et al. 2021). While there has been debate about the nuanced differences among restoration, rehabilitation, and reclamation, in this study we use the definition of ecological reclamation as 'the process of assisting the recovery of severely degraded ecosystems to benefit native biota through the establishment of habitats, populations, communities, or ecosystems that are similar, but not necessarily identical to surrounding and naturally occurring ecosystems' (Gerwing, Hawkes, Gann, & Murphy 2021).

Although different management practices are used to reclaim land based on the initial surface disturbance and other environmental considerations, it is typical of ecological reclamation activities to include soil management and installation of plant material (Bradshaw 1994). It is not uncommon for environmental monitoring programmes to be looked at as costly and unscientific, though sound monitoring has been shown to provide a variety of benefits to improve management practices (Lovett et al. 2007, Lindenmayer & Likens 2010). As the need for reclamation is growing with increased anthropogenic activity, efforts to aid with predicting outcomes have recently been underway, as the ability to limit uncertainty associated with reclamation would likely enhance management practices (Brudvig & Cattano 2021; Bertuol-Garcia et al. 2023). In a recent effort to test predictability models, it was found that a lack of sound, long-term monitoring data was a major limiting factor (Bertuol-Garcia et al. 2023).

Ecological reclamation efforts associated with oil and natural gas development in North America are required to be monitored, though discrepancies in protocol vary between and among government agencies (Curran, Wolff, & Stahl 2013; Curran & Stahl 2015). While it is common for regulatory criteria to focus on vegetation cover, presence or absence of noxious and invasive weeds, and erosion control, more recent efforts have been made to improve ecosystem functionality and wildlife habitat (Stahl & Curran 2017). Efforts to improve reclamation monitoring at the site-specific level have shown that utilizing spatially balanced sampling designs, route optimization, and digital imagery can increase data quality while significantly reducing time spent on a given location (Curran et al. 2019; 2020a). The impetus for these studies was to provide information to operators which not only satisfied regulatory criteria but could assess habitat for various wildlife species and provide improved decision-making capability for practitioners (e.g., better understanding of seed mix performance), thereby satisfying the needs of multiple stakeholders (Curran et al. 2019). Even so, many oil and gas operating companies are responsible for conducting monitoring across vast areas containing many locations. As budget, manpower, and time constraints are common issues associated with completing full censuses during surveys associated with project management, developing long-term monitoring strategies across an entire asset is critical (Kerzner 2013).

Creating monitoring strategies over space and time allows for population parameters to be estimated at distinct time points, for averaging population parameters over time, for measuring both net change and components of individual change, and for the accumulation of samples over time along with other benefits (Duncan & Kalton 1987). Considering both space and time components into sampling designs allows for good spatial coverage at each sampling phase (Hankin, Mohr, & Newman 2019). Rotating panel designs have proven useful for environmental surveys and require the creation of a panel (i.e., a group of population units which are always sampled during the same time period), a revisit design (i.e., a plan for units to be visited and sampled over time), and a membership design (i.e., the way in which units of the population become members of the design) (McDonald 2003). Membership design has often been flawed by haphazard (i.e., collected without a defined protocol) or judgement (i.e., subjectively selected by the observer) sampling which are both examples of non-probability sampling and result in issues with statistical validity (McDonald 2003).

Probability sampling techniques which would be improvements over haphazard or judgement sampling include simple random sampling, systematic sampling, and spatially balanced sampling (Hankin, Mohr, & Newman 2019). As it is common for nearby environmental units to be influenced by similar biological and abiotic factors, sampling designs which are spatially well balanced are often most appropriate for environmental monitoring (Stevens & Olsen 2004, Robertson et al. 2013, 2017, Kermorvant et al. 2019). Across an entire natural gas field, it is also not uncommon for locations near each other to be seeded at similar times or with similar seed mixes and to be influenced by similar management practices (e.g., grazing), soil properties, and surrounding vegetation.

The Pinedale Anticline natural gas field in Sublette County, WY, USA covers ~81,000 hectares, experiences and average of 42 frost-free days per year and contains over 300 natural gas well pads and a pipeline right-of-way (ROW) system, which is an infrastructure network, transporting natural gas and liquids. After construction of a well pad is complete and no longer needed for initial well activity (or drilling and completion activity), it is typical to see ~70-80% of the area begin a process of interim reclamation with the remaining portion of the well pad going into final reclamation at the end of the pad's life cycle (Curran & Stahl 2015), whereas the entire pipeline ROW system sees reclamation initiated over the entirety of surface disturbance soon after the pipeline is buried and soil is replaced. The short growing season coupled with low and unpredictable precipitation creates a narrow timeframe to conduct monitoring to assess vegetation performance on reclamation sites. In effort to create a long-term monitoring strategy across the entire field, a rotating panel design using spatially balanced sampling principles was applied to both the well pad and pipeline ROW system.

The purpose of this paper is to demonstrate the creation of a spatially balanced rotating panel design utilizing a one-point-per-cluster sampling methodology. We focus on a terrestrial natural gas field and give examples of how this methodology can be applied across patches within a landscape and linear features within a landscape. We discuss the creation of spatially similar neighbourhoods and the development of a rotating panel using one-point-per-cluster sampling in Section 2. In Section 3, we demonstrate the utilization of this approach within a natural gas field in the western United States with application to both well pads and pipeline ROWs. We then discuss advantages of this approach and how it can be applied to other ecosystems.

# 2 | MATERIALS AND METHODS

## 2.1 Rotating Panel Design

This section proposes a rotating panel design for surveying through time. Each panel contains a sample of $n$ units from a finite

$$\sum_{j \in s} I(j \in B(i,r)) \approx \frac{n}{N} \sum_{j \in U} I(j \in B(i,r))$$

population $U = \{1, \ldots, N\}$, where unit $i$ has inclusion probability $\pi_i = n/N$ for all $i$. We assume spatial locations $\mathbf{x}_i \in R^2$ are available for all $i \in U$, and that $N \geq n\gamma$ where $\gamma$ is the number of panels. Ideally, each panel is a scaled-down version of the entire population, where the panel reflects the population in as many ways as possible. Let $B(i, r)$ be a ball with center $i \in U$ and radius $r > 0$. An equal probability sample $s \subset U$ is considered well-spread and representative if

for all $i$ and $r$, where $I(x) = 1$ when condition $x$ is true and 0 otherwise (Grafström and Lundström 2013, Grafström and Schelin 2014). We focus on spatially balanced, representative samples to define each panel.

Our rotating panel design defines its panels using the one-point-per-cluster spatially balanced design proposed by Robertson and Price (2024a). This design is particularly interesting because it allows us to define panels that are spatially similar. Initially, a simple random sample (SRS) of $N^* = \lambda n$ units is drawn from $U$, where $\lambda \geq \gamma$ is a sufficiently large integer satisfying $\lambda n \geq N$ (Robertson and Price 2024a). These units are numbered 1, …, $N^*$ for clarity. Then, the SRS is clustered into $n$ spatially contiguous clusters, each containing $\lambda$ units, using the constrained $k$-means algorithm proposed by Robertson and Price (2024a). This is an optimization problem of the form

$$\begin{array}{ll} \text{minimize} & \sum_{k=1}^{n} \sum_{i=1}^{N^*} z_{ki} \|\boldsymbol{x}_i - \boldsymbol{m}_k\|^2 \\ \text{subject to} & \sum_{i=1}^{N^*} z_{ki} = \lambda, \forall k = 1, \ldots, n \\ & \sum_{k=1}^{n} z_{ki} = 1, \forall i = 1, \ldots, N^* \\ & z_{ki} \in \{0,1\}, \forall i, k, \end{array}$$

where $\boldsymbol{m}_k$ is the mean of the $k$th cluster. The first constraint forces $\lambda$ units in each cluster, and the second ensures each unit is assigned to a cluster. This problem can be solved efficiently using the iterative method described in (Robertson and Price 2024a).

Using the clustered units, $\lambda$ distinct one-point-per-cluster candidate samples are defined, each containing one unit from each of the $n$ clusters. Rather than randomly assigning units to candidate samples, Robertson and Price (2024a) use a linear assignment strategy that optimizes the average spatial spread of the candidate samples. To define an objective measure of sample spread, we use modified Moran's $I$ (Tillé et al. 2018). After the assignments are made, each candidate is an equal probability spatially balanced sample from $U$ (Robertson and Price 2024a), and randomly choosing $\gamma$ of them without replacement defines our distinct panels.

A desirable feature of this approach is that each panel is spatially balanced and representative. A substantial body of the literature on sampling methodology has shown that when response variables exhibit spatial trends, spatially balanced samples improve the precision of commonly used design-based estimators (c.f. Stevens and Olsen 2004; Grafström and Lundström 2013; Grafström and Schelin 2014). Hence, valuable estimates of population characteristics are possible from each panel. Secondly, the panels are spatially similar and guaranteed to contain a unit from specific geographic areas (one unit from each spatially contiguous cluster). Hence, at each sampling phase, assessment of local change is possible.

## 2.2 Estimation

Let $y_i$ be the response value for the $i$th unit, with population total $\tau = \Sigma_i y_i$. The Horvitz-Thompson (HT) estimator

$$\hat{\tau} = \sum_{i \in s} \frac{y_i}{\pi_i}$$

is an unbiased estimator of $\tau$ for panel $s$ because each panel is a probability sample from $U$ (Robertson and Price 2024a). However, an unbiased estimator of the variance of the HT estimator is not always possible because second-order inclusion probabilities for nearby units can be zero when forcing spatial spread (Grafström et al. 2014; Robertson et al. 2018). Two first-order estimators for spatially balanced samples are the local mean variance estimator (Stevens and Olsen 2003) and a squared local deviations method proposed by Grafström and Schelin (2014). Spatially balanced resampling methods have also been proposed to estimate the variance of the HT estimator (Robertson et al. 2021, 2022; Ozturk et al. 2023).

# 3 | APPLICATION: PINEDALE ANTICLINE NATURAL GAS FIELD ECOLOGICAL RECLAMATION AREAS

In this section, we present two spatially balanced rotating panel applications. The first considers sampling well pads in the Pinedale Anticline natural gas field (see Figure 1), and the second samples a natural gas pipeline (see Figure 2). Reclamation efforts in the Pinedale Anticline natural gas field are regulated by the Wyoming Department of Environmental Quality and the Department of Interior – Bureau of Land Management (BLM) 2008 Record of Decision for Supplemental Environmental Impact Statement (SEIS) for the Pinedale Anticline Project Area (PAPA). The BLM 2008 ROD SEIS PAPA created an interagency governmental consortium of State and Federal regulatory bodies to ensure reclamation efforts in the area result in lack of noxious weeds, presence of native plant diversity similar to background conditions, and minimal erosion features. It is required for operating companies to perform quantitative monitoring on 10% of their asset on an annual basis. In addition to abiding by regulatory requirements, operators may benefit from monitoring data if it assists their ability to understand how reclamation practices (e.g., seed mixes, soil amendments) are performing and if they can leverage data for other uses (e.g., to assess wildlife habitat).

## 3.1 Pinedale well pads

The Pinedale field has $N$ = 303 well pads distributed across a sparsely populated area of southwest Wyoming. The monitoring programme is to be conducted over five years (2022-2027) with one sampling phase each year. Resourcing is available for field practitioners to survey $n$ = 60 pads at each sampling phase. The design goals are to achieve a spatial balance at each sampling phase and to cover the field (approximately) over the monitoring period. Each sampling phase provides the ability to quantitatively monitor ~20% of the asset, doubling regulatory expectations.

Initially, an SRS of $N^* = \lambda n$ = 5 x 60 = 300 well pads were selected from the Pinedale field (three pads randomly excluded from the monitoring programme). These pads were clustered into $n$ = 60 spatially contiguous clusters (see Figure 1), each containing $\lambda$ = 5 pads, using the constrained $k$-means algorithm (Robertson and Price 2024a). Five distinct one-point per-cluster samples containing 60 pads each were constructed from the clustered pads to minimize the average modified Moran's $I$ (Robertson and Price 2024a). Each sample is an equal probability spatially balanced sample from the Pinedale field (Robertson and Price 2024a). In this application, $\gamma = \lambda = 5$, so these five samples define the five panels for the monitoring programme, with one of the panels illustrated in Figures 1 & 3. The panel is well-spread over the field.

At each well pad, a spatially balanced sample design called balanced acceptance sampling (BAS; Robertson et al. 2013), was used to generate locations from which to collect quantitative information (described in Curran et al. 2019). An optimal route was generated by solving the traveling salesman problem so that each BAS location was visited as efficiently as possible (Curran et al. 2020ab; Figure 5). A cellphone application called Field Maps (ESRI; Redlands, CA, USA) was used to navigate to BAS locations and a $1m^2$ nadir image was taken at each location for subsequent analysis in SamplePoint (Booth et al. 2006), a free software used to manually classify pixels within images. Vegetation within images can be classified to the species-specific level and subsequent queries can be used to assess seed mixes, determine if locations meet regulatory criteria across agencies, evaluate wildlife habitat and biodiversity metrics, and identify problematic areas (e.g., weed presence) at a given well pad (Curran et al. 2019, 2020a). Since they are also geo-tagged, these images can also be used to direct regulatory agents or other contractors (e.g., herbicide applicators) to areas of concern (Curran et al. 2019). Given that images are permanent records, they can be analyzed by multiple users or new software as it arises. As each panel is visited, data can be used to identify trends within neighbourhoods and better understand reclamation outcomes across the entire field. Furthermore, as the image repository grows it is likely that images can be used to inform new software development (e.g., supervised learning models to reduce the need for manual classification).

## 3.2 Pipeline Right-of-way

The Pinedale pipeline is a linear resource, approximately **21** km long. This pipeline was discretized into $N$ = 146 sections of equal length, with the central point of each section defining a point resource sampling frame (see Figure 2). Sampling takes place over the same five-year period as above (2022- 2027), with one sampling phase each year. Resourcing is available for field practitioners to survey $n$ = 29 sites in each sampling phase. The design goals were similar to the well pad application above, where spatial balance and pipeline ROW coverage were desirable. Again, covering 20% of the area of interest doubles the requirement of regulatory agencies.

Initially, an SRS of $N^* = \lambda n$ = 5 x 29 = 145 sites were selected from the pipeline (one site randomly excluded from the monitoring programme). These sites were then clustered into n = 29 spatially contiguous clusters (see Figure 2), each containing $\lambda$ = 5 sites, using the constrained $k$-means algorithm (Robertson and Price 2024a). Five distinct one-point-per cluster samples containing 29 sites were constructed from the clustered sites to minimize the average modified Moran's $I$ (Robertson and Price 2024a). Each sample is an equal probability spatially balanced sample from the discretized pipeline ROW (Robertson and Price 2024a). In this application, $\gamma = \lambda = 5$, so these five samples define the five panels for the monitoring programme, with one of the panels illustrated in Figure 2 & 3. The panel is well-spread across the pipeline ROW.

Similar to the well pad example, BAS and route optimization is used within each section of pipeline ROW to navigate to points at which to take 1m$^2$ images which are then classified within SamplePoint. The same information gathered at well pads can be applied to pipeline ROWs and assist with overall decision making while satisfying the needs of multiple stakeholders.

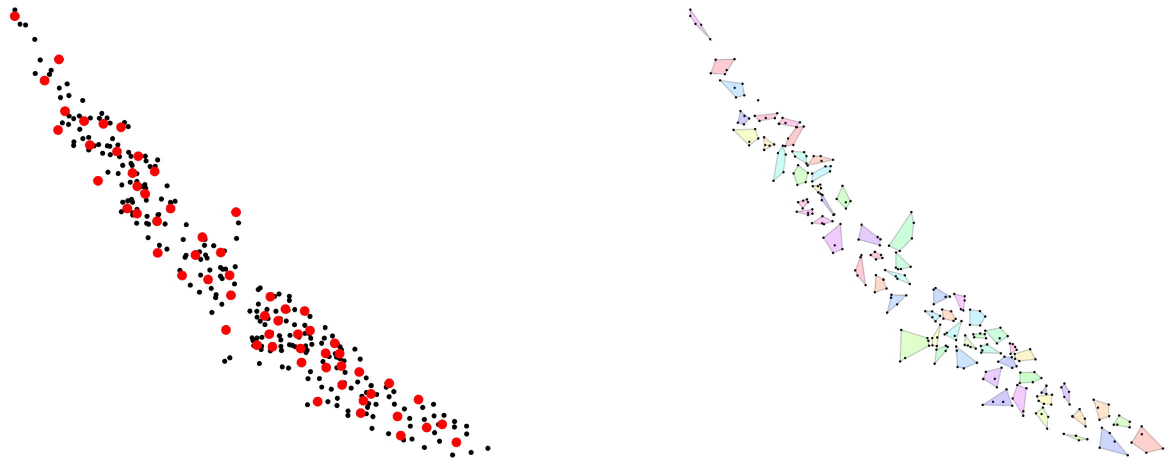

FIGURE 1: (left above) Pinedale well pad locations (black) and one panel of *n* = 60 spatially balanced sites (red). (right above) Spatially contiguous clusters (colored polygons). Each panel contains one well pad from each polygon.

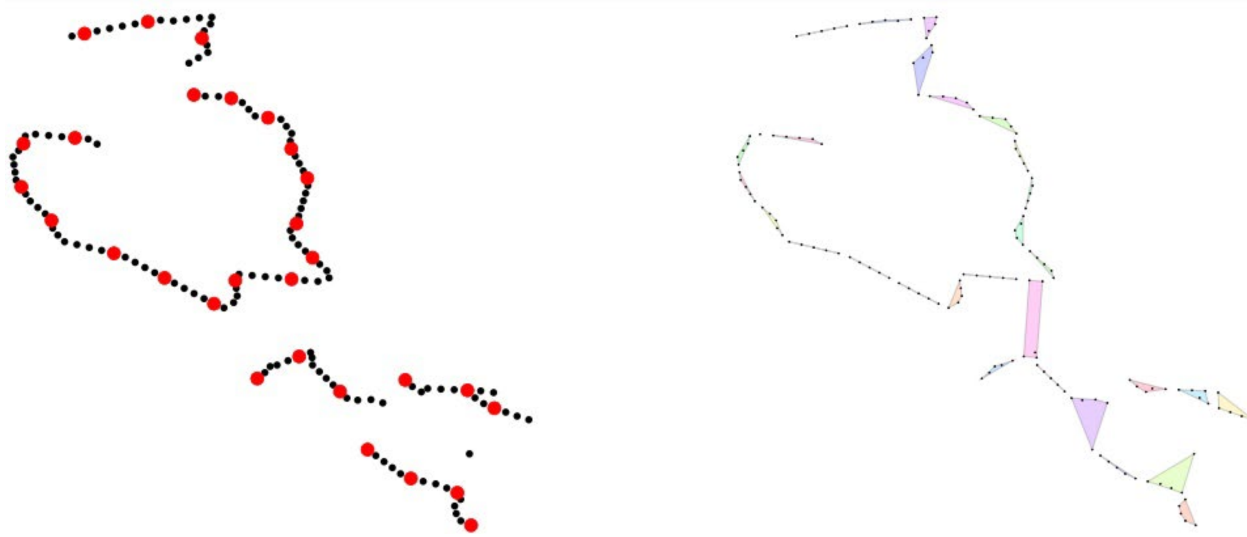

FIGURE 2: (left above) Pipeline site locations (black) and one panel of *n* = 29 spatially balanced sites (red). (right above) Spatially contiguous clusters (colored polygons). Each panel contains one well pad from each polygon.

## 4 | DISCUSSION

Spatially balanced sample designs at individual reclamation sites provide numerous benefits in time- and cost-reduction, while improving data quality and satisfying multiple stakeholder and regulatory needs (Curran et al. 2019, 2020). Incorporating spatially balanced sampling concepts across an entire management area and combining a temporal component provides additional benefits. Previous research aiming to identify trends in vegetation response to ecological reclamation related to oil and natural gas development proved difficult as monitoring strategies, timing and field technicians often change from year to year (Curran and Stahl 2015). As it is common for personnel changes to occur among stakeholder groups (e.g., regulatory agencies, operating companies, consulting firms), a spatially balanced sample with defined panels and sampling phases can be used as a master sample and reduce the risk of haphazard restarts in monitoring programmes (van Dam-Bates et al. 2017).

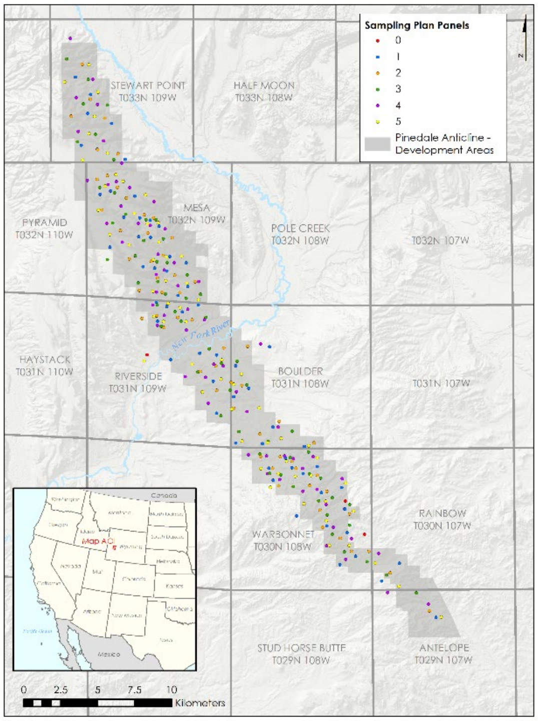


FIGURE 3: A map view of how well pad panels are spread over the Pinedale Anticline natural gas field.

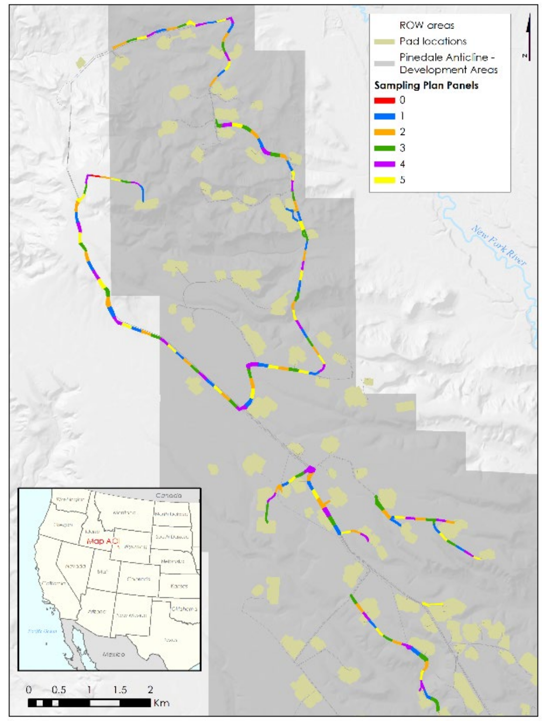


FIGURE 4: A map view of how pipeline right-of-way panels are spread across the Pinedale Anticline natural gas field.

In addition to reducing haphazard sampling across a large area, our design exceeds regulatory criteria and allows for field monitoring to be conducted by a small team in a short duration (e.g., all 60 well pads in this study were able to be monitored by one individual in less than 2 weeks). As transportation cost is often the most expensive component of vegetation surveys at large-scale (Stohlgren, Bull, Otsuki 1998), long-term monitoring plans which allow for rapid field data collection are likely to reduce overall operational costs. In addition to cost- and time-savings, the ability to collect large amounts of information rapidly is especially valuable in areas which have short growing seasons with narrow plant phenological windows (Morrison 2016, Curran et al. 2019).

Furthermore, because our design is spatially well balanced, the ability to make estimates about reclamation performance on a field-wide scale is enhanced (van Dam-Bates et al. 2017). This is likely to benefit operators or agencies relying on data to make management decisions at a field-wide level (e.g., understanding areas where reclamation is resulting in suitable wildlife habitat). Coordinated efforts between upstream and midstream operating companies are beneficial to reclamation, since understanding the interconnectedness of land surface on well pads and pipeline ROW is critical to assessing ecosystem functionality. As data is collected consistently over time, the ability to improve future reclamation practices at the field-wide level should also be expected to improve, as information gathered can be used to create predictive models based on various environmental factors and reclamation inputs (Bertuol-Garcia et al. 2023).

Although our study was limited to the Pinedale Anticline natural gas field, the methodology we propose can easily be applied to other areas which require long-term ecological monitoring. Our design guarantees local coverage during each sampling phase, achieves equal inclusion probabilities, and has excellent spatial spread. While this framework can be used to guide long-term ecological strategies across space and time, it is important for various stakeholder groups to collaborate to ensure data collection at the site-specific level satisfies the needs of various entities (Reynolds et al. 2016). It should also be noted that while we used a 5-year rotating panel to visit all locations within our area of interest, other revisitation structures are possible and may be beneficial in other ecosystems (e.g., McDonald 2003).

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## AUTHORS' CONTRIBUTIONS

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### DATA ACCESSIBILITY

Data and code will be made available upon reasonable request.

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