Natural recovery of soil organic matter in 30–90-year-old abandoned oil and gas wells in sagebrush steppe

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Citation: Avirmed, O., I. C. Burke, M. L. Mobley, W. K. Lauenroth, and D. R. Schlaepfer. 2014. Natural recovery of soil organic matter in 30–90-year-old abandoned oil and gas wells in sagebrush steppe. Ecosphere 5(3):24. http://dx.doi.org/10.1890/ES13-00272.1

Abstract. We addressed the rarely studied issue of how different soil organic matter pools respond to disturbances from historical oil and gas well development in semi-arid Intermountain sagebrush steppe. We selected twenty-nine study well sites in south-central Wyoming that were plugged and abandoned 33–90 years ago. We designed our study to understand the long term impact of oil and gas development for soil organic matter pools on non-reclaimed sites, and evaluate the importance of this disturbance type relative to other major influences on soil organic matter and the fine-scale, shrub-induced heterogeneity of soil organic matter. We compared total, labile, and recalcitrant pools of soil C and N in disturbed sites to adjacent, un-disturbed sites. We found that that natural site-specific conditions such as soil texture and fine-scale heterogeneity associated with shrubs are the most important controls over soil C and N, particulate organic matter C and N, and potential C and N mineralization, and that these older well-pad disturbances did not have a significant effect on any soil organic matter pools. Fine-scale, shrub-induced heterogeneity was higher for those pools that have a fast turnover rate than those with a slow turnover rate. Moreover, fine-scale heterogeneity of total soil C was higher for well sites that were located in loamy sand soils compared to well sites on sandy soils. In addition, heterogeneity of total soil C recovered through time on the finer textured soils. Overall our study suggests that soil organic matter pools were not affected by old oil well development, and that recovery of shrub cover is a key component of soil organic matter recovery in these semi-arid shrublands. A comparison of our work to other work on recent and reclaimed sites suggests that some reclamation procedures may decrease soil organic matter more than the absence of reclamation.

Key words: active pool; disturbance; intermediate pool; oil and gas development; particulate organic matter; recovery; sagebrush steppe; shrub-induced heterogeneity; soil organic matter; succession.

INTRODUCTION

Global energy demand has increased by almost 50% in the last 30 years, and it is projected to expand rapidly by another one third between now and 2035 (IEA 2013). Fossil fuels, including petroleum, natural gas and coal, remain the largest source of energy. In the USA, the high demand for energy has resulted in a rapid boom of oil and natural gas extraction projects in the
late twentieth and early twenty-first centuries. For example, in the Intermountain West, oil and gas development doubled from 1990 to 2007 and is predicted to increase by approximately 4 million impacted hectares in the next two decades (Anderson et al. 2009, Copeland et al. 2009). The majority of the impacted areas within the Intermountain West region are part of the sagebrush steppe ecosystem, a system that once covered as much as 60 million ha in North America (Kuchler 1970, Schlaepfer et al. 2012). Because of the spatial extent of sagebrush, its rapid rate of change, and the vulnerability of key sagebrush ecosystem services (Knick 1999, Knick et al. 2003), it is critical to understand the past impacts of oil and gas development, with implications for managing future such development. In this paper, we focus on soil organic matter change as a consequence of oil and gas development. We address two inter-related key components: total soil organic matter change, and the fine-scale spatial heterogeneity of soil organic matter changes.

A recent inventory of North American carbon (hereafter C) pools found that C pools in semi-arid shrubland soils were studied less than in any other ecosystem (King et al. 2012). Much of the carbon in semi-arid ecosystems is present in soil organic matter, which is spatially heterogeneous at scales from individual plants to landscape and regional scales (Burke 1989). Within similar climatic and management conditions of the sagebrush steppe, soil texture, topography and their interactions play a significant role in controlling the distribution of soil organic matter pools and fluxes (Burke 1989, Burke et al. 1989c, Burke et al. 1995a). Net primary productivity, the process responsible for inputs into soil organic matter, is strongly determined by topography in sagebrush steppe, with highest vegetation cover, net primary productivity, and thus soil organic matter where snow accumulates (leeeward slopes and toeslopes), in depressions, and on north-facing slopes (Burke et al. 1989a). Fine-textured soils also tend to have higher soil organic matter than sandier soils, likely due to slower decomposition rates (Burke 1989).

There is also a strong variability of soils in semi-arid ecosystems associated with the location of individual plants (Charley and West 1975, 1977, Burke et al. 1989a, Burke et al. 1989b, Hook et al. 1991, Schlesinger et al. 1996, Burke et al. 1998, Sankey et al. 2012a). This fine-scale heterogeneity in soil organic matter, which is concentrated under individual shrubs relative to interspaces, is a well-recognized feature of sagebrush ecosystems, with indications that it is responsive to changes in ecosystem management (Burke et al. 1987, Sankey et al. 2012b).

Oil and gas exploration and extraction replace natural habitats with infrastructure, including well pads and roads, with a high potential for altering soil organic matter. The historical and contemporary effects of such development on soils are not well studied. Contemporary well pad development procedures since the Surface Mine and Conservation Act of 1977 (hereafter SMCRA) include complete removal of vegetation and the soil, and underlying bedrock is excavated during well site development (Shrestha and Lal 2011, Dangi et al. 2012). Management of well sites preceding SMCRA did not include these well site preparation and reclamation practices, to our knowledge. More is known about soil responses to energy development and reclamation associated with coal mining, disturbances with a different spatial pattern and extent than the disturbances associated with oil and gas well site development. In one-year-old stockpiles (topsoil piled for storage and planned to be moved again later) associated with coal mining, Wick et al. (2009) measured up to 75% less C in micro- and macro-aggregates; C in these pools did not recover after 16 years. Soil microbial biomass in the same one-year-old stockpiles was also 50% less than undisturbed areas, and it recovered in five years (Dangi et al. 2012). However, these results are not directly applicable to oil and gas well developments and the effect of current or past management on soil organic matter and its recovery is not well understood.

In semi-arid ecosystems, there have been more studies that addressed soil organic matter recovery after other types of disturbances. For example, a post-cultivation study in northwestern Utah found that fine-scale heterogeneity recovered after 90 years, but total soil biogeochemical pools did not (Morris et al. 2013). Post-cultivation recovery in shortgrass steppe that has similar climatic conditions also showed slow recovery of soil organic matter even after 50 years (Burke et al. 1995b). A study of the effects of oil and gas
development on soil organic matter in sagebrush is important for two reasons. First, there is little knowledge about long-term recovery of soil organic matter in dry shrubland ecosystems. Second, it is important to understand the consequences of the recent rapid increase in oil and gas extraction.

Here we describe the long-term natural recovery of soil organic matter pools at old oil and gas well sites. The well sites were plugged and abandoned between 1923 and 1980. Assuming that the original disturbances were roughly similar, we could use the chronosequence to infer the rate of recovery of soil organic matter following disturbance. We also assumed that during the original disturbance, all fine-scale heterogeneity associated with individual plants was eliminated (Burke et al. 1987). We asked: (1) How important is past disturbance by oil and gas development relative to other important controls over soil organic matter in sagebrush ecosystems? Specifically, what is the relative importance of disturbance from oil and gas development compared with soil texture and plant-induced fine-scale heterogeneity for the distribution of soil organic matter? (2) How was soil organic matter affected by oil and gas development from pre-reclamation practices, and how quickly does soil organic matter recover in the absence of reclamation? And in areas where sagebrush vegetation has recovered, what is the rate of recovery of fine-scale heterogeneity?

**Materials and Methods**

**Site Description**

The study area was located in Carbon and Sweetwater counties of Wyoming, USA (41°23’ to 42°23’ N and 107°34’ to 107°89’ W). The area is typical of the sagebrush steppe in Wyoming, where vegetation is dominated by Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young). Other plant species present are black sagebrush (*Artemisia nova* A. Nelson), green needlegrass (Nassella viridula (Trin.) Barkworth), western wheatgrass (*Pascopyrum smithii* (Rydb.) A. Löve), Greene’s rabbitbrush (*Chrysothamnus greenei* (A. Gray) Greene) and rubber rabbitbrush (*Ericameria nauseosa* var. *oreophila* (A. Nelson) G.L. Nesom & Baird) (West 1983, Driese et al. 1997).

The study area is characterized by Typic and Lithic Torriorthent soils with mesic and aridic moisture regimes, with textures characterized as sandy loam or sandy (Munn and Arneson 1998). Mean annual precipitation across the region encompassing these well sites ranges between 215-343 mm and mean annual temperature ranges between 5.5° and 6.0°C. A larger proportion of precipitation falls in winter months than summer (PRISM 2011).

We used the Wyoming Oil and Gas Conservation Commission (WOGCC 2010) database to identify 29 oil and gas well sites that were plugged and abandoned between 1918 and 1980. We verified the identity of each well site in the field with information on the metal post in the center of the well sites. None of the sites showed evidence of site preparation or reclamation activities, which would have been evident by the presence of non-native varieties used in reclamation during the era (e.g., *Agropyron cristatum*), even distribution of individual plants, removal of discarded equipment, or soil preparation.

Our goal in locating older well sites was to represent variability in the region to maximize the realm of inference of our study. Variability among sites is well-recognized as a limitation to chronosequence studies, which attempt to use space as a substitute for time (Pickett 1989), thus tracking the variability while maximizing our realm of inference was important. The well sites fall into two clusters. The first cluster is located between the towns of Baggs and Wamsutter (hereafter referred to as the southern cluster) and the second cluster of well sites is between Rawlins and Bairoil (northern cluster) (Fig. 1). Most of the older well sites are located in the northern sites, while most of the younger sites are located in the southern cluster. The northern well sites are dominated by sandy soils (Table 1), located on dune sand and loess, and the southern cluster by sandy loam soils, located on shale with sandstone beds (Mesaverde Formation) (WSGS 2013). As a result, there was a strong co-variation of soil texture with the age of the well sites.

**Field Sampling**

For each well site, with an average disturbance area of about 1300 m² (20 m radius), we established three transects in NW, SW and SE
directions. Along each transect, we selected two plots: one 4 m from the center point (in the disturbed area) and the second 24 m away from the center point (in the undisturbed area). In each plot, we sampled soil profiles underneath the shrub canopy and between shrubs for a total of 12 profiles per well site. For each of the 12 profiles, we collected soil samples in interspaces between shrubs at 0–5 and 5–10 cm depths using a soil corer in the summer of 2010 (hereafter “surface soils”). For profiles that were collected under shrub canopies, we separately measured the height of the raised areas below shrubs (the “humps”), and sampled from them, then sampled from the “0” level for 0–5 and 5–10 cm depths. Thus, surface soils from under shrub locations had 3 depth increments (“hump”, 0–5 cm, and 5–10 cm), while those between shrubs had 2 depth increments (0–5 and 5–10 cm). These surface soil samples were transferred to the laboratory in cold containers and refrigerated until laboratory analysis. During the summer of 2011, we sampled from 0–20, 20–40 and 40–60 cm depths (subsurface soils).

Surface soil samples from all transects at each site were grouped according to depth, disturbance conditions (inside or outside the well pad),

Table 1. Soil texture in 29 33–90-year-old abandoned oil and gas well sites in south-central Wyoming, in southern and northern clusters. Values are means across well-sites with corresponding SEs.

| Shrub location | Depth | Sand   | Clay     | Silt     |
|----------------|-------|--------|----------|----------|
| Southern       |       |        |          |          |
| Disturbed      |       |        |          |          |
| Between        | 0–5 cm| 64 ± 2.5| 11 ± 0.9 | 24 ± 2.1 |
|                | 5–10 cm| 66 ± 2.3| 12 ± 0.9 | 22 ± 1.9 |
| Shrub          | 0–5 cm| 66 ± 2.2| 12 ± 1.0 | 22 ± 2.0 |
|                | 5–10 cm| 64 ± 2.1| 11 ± 0.8 | 25 ± 1.7 |
| hump           | 69 ± 1.8| 9 ± 0.8 | 21 ± 1.7 |          |
| Undisturbed    |       |        |          |          |
| Between        | 0–5 cm| 68 ± 2.3| 10 ± 0.8 | 22 ± 1.8 |
|                | 5–10 cm| 65 ± 2.1| 12 ± 0.8 | 23 ± 1.7 |
| Shrub          | 0–5 cm| 66 ± 2.2| 10 ± 0.9 | 23 ± 1.7 |
|                | 5–10 cm| 66 ± 2.2| 12 ± 0.9 | 22 ± 1.9 |
| hump           | 71 ± 2.0| 9 ± 0.7 | 20 ± 1.9 |          |
| Northern       |       |        |          |          |
| Disturbed      |       |        |          |          |
| Between        | 0–5 cm| 85 ± 1.2| 7 ± 0.5  | 8 ± 0.8  |
|                | 5–10 cm| 85 ± 1.2| 7 ± 0.5  | 8 ± 0.8  |
| Shrub          | 0–5 cm| 85 ± 1.1| 7 ± 0.4  | 8 ± 0.8  |
|                | 5–10 cm| 85 ± 0.9| 7 ± 0.3  | 8 ± 0.8  |
| hump           | 87 ± 1.1| 6 ± 0.5 | 7 ± 0.7  |          |
| Undisturbed    |       |        |          |          |
| Between        | 0–5 cm| 87 ± 1.0| 7 ± 0.7  | 7 ± 0.6  |
|                | 5–10 cm| 85 ± 1.0| 7 ± 0.4  | 8 ± 0.7  |
| Shrub          | 0–5 cm| 86 ± 1.0| 7 ± 0.6  | 7 ± 0.7  |
|                | 5–10 cm| 86 ± 1.1| 6 ± 0.5  | 8 ± 0.8  |
| hump           | 88 ± 0.8| 4 ± 0.2 | 7 ± 0.7  |          |

Fig. 1. Abandoned oil and gas wells in south-central Wyoming (gray dots). Those included in our study (blue dots) were clustered into two areas: the northern well sites, with a sand content of 86 ± 7% (mean ± SE), and the southern well sites, with an average sand content of 64 ± 14%. County borders, major roads, and several cities are included as geographic reference (map coordinates are longitude/latitude).
and position with respect to individual shrubs (under or between shrub canopies). For each group, we made one composite soil sample by combining soil samples, such that one composite for each well pad, disturbance, microsite and depth was formed. Because our true replicates were the individual oil pads, maintaining data on the variability associated with individual sub-samples did not gain us any degrees of freedom for the analysis. These composite soils were used to analyze active and intermediate pool C and nitrogen (N).

Laboratory analysis

Soil bulk density was estimated at disturbed and undisturbed plots using an independent soil sample from the 0–5 cm depth, the depth most likely to be influenced by the well development. We sampled randomly across microsites to generate a weighted mean. Fine soil bulk density was calculated using total mass and total sample volume after the soil was sieved to 2 mm and air-dried, in order to convert C and N concentrations to volumetric measures. We estimated soil texture for each sample using the hydrometer method (Bouyoucos 1962).

Soil organic matter is conceptually divided into compartments based on decomposition kinetics (Jenkinson and Rayner 1977, Parton et al. 1987). These conceptual pools have been shown to correlate to empirically measurable pools (Kelly et al. 1996), each with distinct characteristics with respect to sensitivity to, and recovery from, disturbance (Cambardella and Elliott 1992).

Active pool.—Active pools, often represented by potentially mineralizable and microbial biomass organic matter, respond and recover faster than other pools (Dangi et al. 2012). We estimated the active pool of soil organic matter as potentially mineralizable C and N in this study (Kelly et al. 1996). A 10-g subsample of soil was used to estimate soil moisture by drying the soils at 65°C for 24 hours. Another 10-g subsample was extracted with K$_2$SO$_4$ to estimate initial inorganic N concentrations. We shook 10 g of soil in 50 ml of 0.5 M K$_2$SO$_4$ for 1 hour, and then filtered the samples with Whatman No. 1 filters. Extracts were frozen until further analysis. A third 10-g subsample of soil was incubated at room temperature for 30 days to estimate potential C and N mineralization. We placed 10 g of soil in plastic measuring cups and brought their moisture levels to 60% pore space wetness using deionized water. Then the containers were placed in 355 ml Mason jars and closed with lids capped with butyl rubber stoppers. The jars were then flushed with CO$_2$ free air for 2 min to get headspace CO$_2$ to near-zero, and incubated for 72 hours at 25°C. This flushing and incubating procedure was repeated at day 14 and 30 (modified from Robertson et al. (1999)). After each 72 hours of incubation, we collected 30 ml of gas from the headspace to estimate CO$_2$ concentration using a LI-820 CO$_2$ gas analyzer (Li-Cor-820, LI-COR Biosciences, Lincoln, Nebraska, USA) calibrated with three standard gases of concentration from 377 to 4500 μmol mol$^{-1}$. Hourly CO$_2$ respiration rate was calculated based on the length of time after flushing. We had six empty jars for controls. At the end of the incubation, we extracted the soils with 0.5 M K$_2$SO$_4$ to estimate potential N mineralization, which we calculated as the difference between final and initial total inorganic nitrogen pools.

Intermediate pool.—Particulate organic matter (hereafter POM) corresponds to an intermediate turnover soil organic matter pool, which responds to decade-long disturbances such as the removal of aboveground biomass (Kelly et al. 1996). We estimated coarse and fine POM following the procedure described in Kelly et al. (1996), based on methods developed by Cambardella and Elliott (1992). We shook 20 g of composited soil in a 0.5 M sodium hexametaphosphate solution for 18 hours and then wet sieved the soil through 53 μm and 0.5 mm mesh sieves with deionized water. The materials in each sieve were dried overnight at 55°C and then homogenized in a planetary ball mill before being analyzed for C and N using a Perkin Elmer CHNS/O Elemental Analyzer 2400 Series-2 (Perkin Elmer, Waltham, Massachusetts, USA).

Total soil organic matter.—Subsamples from all soil samples were homogenized with a micro-grinder and analyzed for total C and N using a Perkin Elmer CHNS/O Elemental Analyzer 2400 Series-2. We consider total soil organic matter to represent primarily the slowest, or most recalcitrant pools.
Statistical analysis

Our first question addressed the relative importance of disturbance compared with fine-scale, plant-associated heterogeneity and soil texture. We performed analysis of variance tests with disturbance, shrub location, and their possible interactions as fixed factors and sand content as a co-variable. For each of these factors we estimated effect sizes by calculating eta squared values ($\eta^2$) in order explain how much variation in the response variable (e.g., total soil organic C, POM, mineralizable C) is explained by that particular factor. This is a standardized measure of effect size and is calculated the same way as r-squared values (Kutner 2005).

We planned to use regression analysis of C and N values against the age of the well sites to answer the second question, which focused on the rate of recovery of soil organic matter following well abandonment.

To answer our question about the recovery of fine-scale heterogeneity, we estimated a “heterogeneity ratio” for each of the response variables. As we mentioned earlier, the soil samples were collected from under shrubs and between shrubs, separately. We divided under-shrub values by corresponding between-shrub values to estimate a heterogeneity ratio for each well site and disturbance combination. This ratio allows us to describe fine-scale heterogeneity in each of the disturbed and undisturbed areas of the well sites. We regressed these heterogeneity ratios against age of the well sites to understand how resource islands changed through time.

We performed the statistical analyses using IBM SPSS 19.0 software (IBM, New York, USA), using an alpha level of 0.05.

RESULTS

We anticipated that differences in soil bulk density or texture across the research sites could influence soil organic matter recovery on well pads. Soils in the disturbed areas were not significantly different than undisturbed areas with respect to bulk density (Fig. 2) or soil texture.

As described above, the study sites fell into two clusters, northern sandy sites and southern loamy sites. The southern loamy sites had higher soil organic matter both at the surface and at depth, and we combined the two depths for an integrated analysis.

Factors that determine soil organic matter content: Disturbance vs. soil texture and fine-scale heterogeneity

We found that disturbance from oil and gas development on these older sites was not as important to soil organic matter content as fine-scale heterogeneity and soil texture (Table 2); in fact, there was no significant difference between well pads and adjacent undisturbed areas with respect to any of the soil organic matter pools we measured. Sand content explained approximately 25% and 7% of the variation in total soil C and N, respectively ($p < 0.0001$; Fig. 3), with total C and N decreasing with sand content. Fine-scale heterogeneity explained approximately 20% and 12% of the variation in our model for total soil C and N, respectively, but disturbance failed to explain a significant portion of the variation of total C and N (Table 2, Fig. 3). Total soil organic matter C, but not N, was higher under shrub canopies than between shrubs.

Particulate organic matter fractions showed similar patterns as total soil organic matter C and N (Fig. 4). Soil texture was a significant control over POM-C, explaining approximately 25% of the variation in fine and medium POM-C and ~17% variation of fine POM-N. Disturbance did

Fig. 2. Soil bulk density in 29 oil and gas well sites abandoned 33–90 years ago in south-central Wyoming, grouped by age class. Disturbance did not have a significant effect on soil bulk density, although there was a difference across well sites with different ages, likely due to a correlation with soil texture. Error bars represent ±1 SE of the mean.
not significantly affect any POM fractions. However, the effect of fine-scale heterogeneity was significant for all POM-C fractions and for medium and fine POM-N. This factor explained ~1–4% of the variation of medium and fine POM-C and ~2–4% variation of medium and fine POM-N.

Fine-scale heterogeneity and soil texture both had significant effects on potential C and N mineralization (Table 2, Fig. 5). For these active pools that are highly responsive with a rapid turnover rate, heterogeneity explained the largest portion of the variation, 56–18%, while soil texture explained ~6% variation. Potential C respiration and N mineralization were higher under shrubs than between shrubs.

Table 2. Percent of the variance explained by factors affecting soil organic matter, particulate organic matter (of coarse-, medium-, and fine-textured fractions), and potential C respiration and N mineralization in 33–90-year-old abandoned oil and gas well sites of south central Wyoming.

| Source                | C resp | N min | Coarse | Medium | Fine | Total |
|-----------------------|--------|-------|--------|--------|------|-------|
|                       | POM-C  | POM-N | POM-C  | POM-N  | POM-C| POM-N |
| Sand                  | 6.1    | 6.5   | 0.5    | 2.4    | 26.4 | 2.6   |
| Shrub location        | 56.5   | 18.1  | 0.1    | 0.4    | 4.0  | 4.5   |
| Disturbance           | 0.1    | 0.2   | 0.2    | 1.5    | 0.1  | 1.3   |
| Shrub location × Disturbance | 0.1 | 0.3   | 0.2    | 1.9    | 0.1  | 1.7   |
|                       |        |       | 24.2   | 17.0   | 25.0 | 6.5   |

Notes: The values shown are percent of variance explained by the factor, calculated as the partial $r^2 \times 100$. Values in boldface are significant at an alpha level of $p = 0.05$. Shrub locations are under vs. between shrubs. Disturbance values indicate disturbed vs. undisturbed. Abbreviations are: C resp, potential C respiration; N min, potential N mineralization; POM, particulate organic matter.

![Fig. 3. Total soil organic C (A and C) and N (B and D) in twenty-nine old abandoned oil and gas well sites in south-central Wyoming. The well sites were abandoned 33–90 years ago. Total C and N values are significantly different between the southern (A and B) and northern (C and D) clusters of sites ($p < 0.0001$). Total soil C and N was always significantly higher under shrubs compared with between shrubs ($p < 0.0001$). Error bars represent ± 1 SE of the mean.](image-url)
Recovery of soil organic matter and fine-scale heterogeneity

Our second goal was to find out how soil organic matter was affected by well development from the pre-reclamation era, and estimate how quickly soil organic matter recovered from these disturbances. Since well site disturbance did not have a significant effect on any soil organic matter fraction, the second question was partly irrelevant. However, since the results above showed that shrub-associated fine-scale heterogeneity is a major control over soil organic matter, and all well sites had experienced the removal of shrubs, we tested whether this heterogeneity recovered across the chronosequence, that is, whether heterogeneity was a function of age on the disturbed well site areas, by regressing the heterogeneity ratio of each variable against the age since disturbance for the disturbed sites. First we will describe the patterns of heterogeneity among and across site features, then evaluate the change with age of the site.

*Fig. 4. Coarse, medium, and fine particulate organic matter C (POM-C; panels A, C, and E, respectively) and N (POM-N; panels B, D, and F, respectively) in 0–10 cm soils from oil and gas well sites abandoned 33–90 years ago. Particulate organic matter C was not different between disturbed and undisturbed sites but was significantly different among the two clusters of well sites (p < 0.0001). In addition shrub-associated heterogeneity (between vs. under shrubs) was a significant factor for most POM fractions (p < 0.02). Error bars represent ± 1 SE of the mean.*
The average undisturbed heterogeneity ratio for total soil C (the slowest turnover pool) was 2.60.13 (mean ± SE; dashed line in Fig. 6).

Average undisturbed site heterogeneity ratios were 1.1 ± 0.16, 1.3 ± 0.16, 2.3 ± 0.44, and 2.2 ± 0.10 for fine, medium, and coarse POM-C and potential C respiration, respectively. The ratios for coarse POM and C respiration were significantly larger than for total soil pools or for the finer fractions (p < 0.0001), indicating highest heterogeneity indices for the most rapid turnover soil organic matter pools. The heterogeneity ratios of POM and active pools were not affected by soil texture.

There was a strong pattern of total C recovery associated with soil texture. The soil heterogeneity ratio for total C increased with age of the disturbance for the less coarse soils in the southern sites (Fig. 6), recovering to the undisturbed value after about 45 years. The northern sandy soils did not show any trend of change with age of the well sites, maintaining a very low heterogeneity ratio throughout the record on the disturbed sites.

Fig. 5. Net N mineralization (A) and potential C respiration (B) in 0–10 cm soils from oil and gas well sites abandoned 33–90 years ago. Potential respiration and mineralization were not different between disturbed and undisturbed sites but were significantly different between and under shrubs (p < 0.0001). Error bars represent ± 1 SE of the mean.

The DISCUSSION

Total soil organic matter of the 33–90-year-old well sites did not show any effects from disturbance associated with well site development, but analysis of fine-scaled heterogeneity showed that there is a legacy of disturbance impacts that recovers more quickly on fine- than coarse-textured soils. These two results have important implications for the current burgeoning oil and gas development in the sagebrush steppe.

First, the lack of total organic matter differences between disturbed and undisturbed well pads was an unexpected result, because recent analyses of mineral or coal mining have found soil organic matter reductions of up to 75% (Wick et al. 2009, Mason et al. 2011). Sites in all of these studies underwent reclamation practices. Oil and gas well site soils that experienced stockpiling and re-spreading have been found to have a significant release of inorganic nutrients (Mason...
et al. 2011), likely due to increased decomposition resulting from the disturbance of soil structure. Recent results from coal mining show that reclaimed soils have altered the entire spectrum of soil physical properties including bulk density, porosity, and soil moisture (Shrestha and Lal 2011). The lack of influence of the older well pad development on soil pools may have implications for current reclamation practices.

While we have no data about the specific management practices used at these sites, we are relatively confident that even for the youngest sites, the contemporary practice of removing and stockpiling surface was not used. The lack of difference between disturbed and undisturbed sites for total soil pools suggests that there were no major losses of soil organic matter as a result of the well pad operations, either from decreased net primary production or from increased respiration. Total soil organic matter recovers slowly in semiarid ecosystems (Burke et al. 1995b), and if significant total soil organic matter had been lost, it would likely be evident even in the oldest well pads. That said, more labile pools such as microbial pools or particulate organic matter pools appear to recover over periods of less than 20–50 years in nearby semiarid grasslands and in coal-mined sites of the Powder River Basin (Burke et al. 1995b, Wick et al. 2009, Dangi et al. 2012). Thus labile pools may have been negatively influenced by the older practices, but if so, they have recovered such that there is no evidence of disturbance on these pools. In any case, prior studies showing the effect of removing and stockpiling surface soils on soil organic matter as a reclamation strategy show significantly decreased total soil organic matter pools (Akala and Lal 2001, Wick et al. 2009, Mason et al. 2011), likely due to increased respiration rates. Our results showed that there were no such losses without reclamation, suggesting that consequences of soil handling techniques need further consideration for reclamation standards.

While disturbance from older well pads did not have a significant effect on soil organic matter, we were able to assess the relative importance of soil texture and shrub-induced heterogeneity on pools of soil organic matter from the most recalcitrant (total soil organic matter carbon and nitrogen), to the most labile (coarse POM and potential mineralization/respiration) (Fig. 7). Generally, soil texture explained a larger proportion of variation in slow turnover soil organic matter pools such as total soil organic matter and fine and medium POM fractions (7–25% of variation) than it did for labile pools (~6%). This likely occurred because of the importance of clay particles in physical and chemical protection of soil organic matter. However, fine-scale heterogeneity explained a larger proportion of variation in labile pools such as C and N mineralization (18–56% of variation) compared to the recalcitrant pools (4–20% of variation), likely because these labile pools reflect larger recent litter inputs directly under shrubs. Similar results were obtained by Burke et al. (1995b), who found that in shortgrass steppe, topographic location (and hence, soil texture)
was the most important control on the slower pools, and that heterogeneity induced by individual plants had a large impact on the more labile pools, with management (in this case grazing) having a minor effect on soil organic matter pools.

Site-specific conditions such as soil texture play a significant role in shaping soil organic matter distribution for the areas we sampled in the sagebrush steppe, and in fact, represented the strongest source of variability for in our study (as stated above). This is not surprising, as previous studies have shown a significant role of soil texture in semi-arid ecosystems on multiple continents (Burke et al. 1989c, Paruelo et al. 1998, Evans et al. 2011) resulting from chemical and physical protection of soil organic matter by clay particles. Similar results were reported for sagebrush steppe ecosystems where site specific conditions and individual plant-associated heterogeneity played major role for soil organic matter distribution (Burke et al. 1999). Our study sites were distributed in two areas that had very different soil texture, and the sandier soils had significantly lower total soil organic matter, POM and potential C and N mineralization rates than the sites with finer texture.

Similarly, like other authors working in sagebrush steppe (Charley and West 1975, 1977, Burke 1989, Rau et al. 2009), we found a strong effect of shrub location on soil organic matter, with soils enriched by a factor of ~2 underneath shrubs for total soil organic matter, and 2.2–2.3 for the more labile fractions. Interestingly, enrichment under shrubs was highest for the most labile fractions, coarse POM and potential C mineralization, suggesting that the fine scale heterogeneity associated with individual plants is the major source of C inputs and is the key to the recovery of soil organic matter in the sagebrush steppe.

The strongest effect of oil and gas development on soils in our study was the removal and recovery of heterogeneity, a characteristic feature of sagebrush systems. The pattern of recovery in heterogeneity was strongly affected by soil texture, such that fine-scale heterogeneity did not increase through time in the sandy cluster of sites, while well sites that were located in the loamy area did show a significant trend of increasing fine-scale heterogeneity. Recent vegetation analysis of the same study sites showed slow but significant recovery of sagebrush cover, though no recovery of forbs, over a period of about 80 years (Avirmed et al. unpublished manuscript), and did not show an effect of texture (or cluster) on the rate of recovery. The discrepancy between the recovery of heterogeneity in soil organic matter in sandy soils and sagebrush cover suggests that there is a substantial time lag between soil organic matter recovery and the recovery of sagebrush in sandy soils. However, recovery of heterogeneity in sandy loam soils was comparatively faster with a shorter time lag of about 45 years.

CONCLUSIONS

In summary, we did not see any effect of disturbance in pre-reclamation era oil and gas well development in the sagebrush steppe. These results differ from those for reclaimed areas, which show losses of soil organic matter associated with soil removal and stockpiling. Careful consideration of contemporary practices of soil handling is merited; eliminating the practice of soil removal and stockpiling could reduce losses of soil organic matter. A reduction in shrub-induced heterogeneity, a key characteristic of sagebrush soils, was the most evident effect of unreclaimed well development on soils. This feature recovered most rapidly on fine-textured soils, suggesting that shrub recovery will be key to recovery of soil organic matter, and that this recovery is dependent on soil type.

ACKNOWLEDGMENTS

The first author was funded by Fulbright Science and Technology program. The research was funded by a Wyoming Excellence Chair of Ecology fund awarded to Prof. Ingrid C. Burke.

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