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Potential for Reclamation of Abandoned Gas Wells to Restore Ecosystem Services in the Fayetteville Shale of Arkansas

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Abstract

Unconventional oil and gas (UOG) drilling has expanded rapidly across the United States, including in the Fayetteville Shale formation in north-central Arkansas where drilling began in 2004. As one of the oldest regions of UOG activity in the United States, this area has experienced significant land-use changes, specifically development of natural habitat and agricultural land for gas infrastructure. In recent years, drilling of new wells has stopped and production has declined. By 2017, 1038 wells had ceased production and been abandoned, which makes them eligible for land reclamation. However, most of these sites (80%) have not been reclaimed and continue to cause losses in ecosystem services. If reclamation was performed on lands associated with abandoned infrastructure, we estimate more than $2 million USD annually in agricultural, timber, and carbon sequestration values would be gained. These benefits far outweigh the costs of reclamation, especially since the benefits accrue over time and reclamation is a short-term cost. Our estimates indicate a 2–4 year break-even time period when cumulative ecosystem services benefits will outweigh reclamation costs. We predicted a well-abandonment rate of 155 per year until 2050 when 98% of wells will be abandoned, which indicates great potential for future ecosystem services restoration. Thus, we recommend that Arkansans at the government and citizen level work to restore lands impacted by UOG development in the Fayetteville Shale region so that their value to landowners and society can be recovered, which will enhance long-term economic and environmental benefits.

Keywords Agriculture · Climate regulation · Ecosystem services · Fayetteville Shale · Reclamation · Shale gas

Introduction

Unconventional oil and gas (UOG), defined here as the combination of horizontal drilling and high volume hydraulic fracturing, has expanded dramatically across the United States over the last 15 years. As of 2016, the United States is the largest producer of fossil fuels in the world (Energy Information Administration 2016). The expansion of UOG has impacted landscapes across multiple regions of the United States, including some areas that have not experienced large amounts of human-induced changes in landscape characteristics (Brittingham et al. 2014; Souther et al. 2014; McClung and Moran 2018; McClung et al. 2019). This method of petroleum and natural gas production has been controversial, in particular due to its potential environmental effects (Drohan et al. 2012; Jackson et al. 2014; Meng and Ashby 2014; Meng 2017). These effects include water and air pollution (Tollefson 2012; Burton et al. 2014; Moore et al. 2014), increased seismic activity (Ellsworth 2013), land-use changes (McDonald et al. 2009; Allred et al. 2015; Trainor et al. 2016; Moran et al. 2017; Davis et al. 2018; Walker et al. 2020), fragmentation of habitats (Moran et al. 2015; Langlois et al. 2017; Pierre et al. 2017; Wolaver et al. 2018; Howden et al. 2019), and wildlife disturbances (Jones et al. 2015; Latta et al. 2015; Thompson et al. 2015).

One way of examining the impact of UOG is to measure changes in ecosystem services (ES). Calculations of ES monetize the value of resources and processes in natural landscapes that are beneficial to humans. These services

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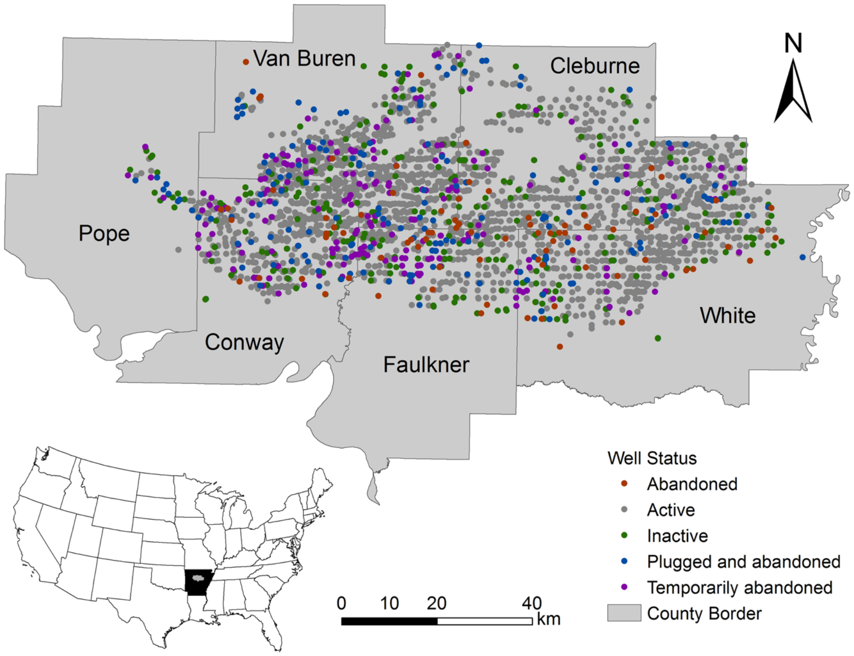

Fig. 1 Map showing the location of wells at various stages of activity across the six counties where the most gas development has occurred in the Fayetteville Shale (shaded in gray)

include valuable assets and processes such as drinking water, raw materials, recreational opportunities, carbon storage, moderation of climate, and maintenance of biodiversity, all of which have measurable benefits to human societies. These ES have been estimated to be worth over $100 trillion annually at a global level (Costanza et al. 2014). The ES costs from UOG in the United States alone, defined as those ES lost due to land development and modification, have been estimated at over $250 million annually and rising as the industry continues to expand across the landscape (Moran et al. 2017). Three major ES impacted by drilling and associated land development include losses in agriculture, timber, and the carbon cycle (Allred et al. 2015).

Similar to other regions of fossil fuel extraction, as UOG areas mature, hydrocarbon production declines (Höök et al. 2009) and the number of abandoned and nonproducing wells increases. Therefore, after a well is no longer producing economic benefits through resource production, it is still costing society through the loss of ES (Jordaan et al. 2009), as well as other negative environmental impacts (notably, fugitive methane leakage, Dilmore et al. 2015; Boothroyd et al. 2016). One method of mitigating ES costs from the fossil fuel industry is the reclamation of the land associated with abandoned and/or nonproducing wells (McFarland et al. 1987). Reclamation involves the removal of well infrastructure (e.g., pumps, well pads, roads, and other supporting structures), site preparation, and the reestablishment of ecosystem-specific native vegetation. Over time this vegetation development can allow the recovery of ES (Chazdon 2008; Evans et al. 2013; U.S. Forest Service 2015), although past impacts are likely to be long-lasting (Matthees et al. 2018; Rottler et al. 2018).

The Fayetteville Shale formation, which contains unconventional gas deposits, is located in north-central Arkansas and eastern Oklahoma and was one of the first locations where UOG developed in the United States. There was conventional gas drilling in the geographic region prior to 2004 ($N = 567$ wells), but it mostly occurred in other geological formations. The vast number of these conventional wells ($N = 427$) were in Pope County (Enverus 2017), which is a county on the western edge of our study region with only a small number of unconventional wells (Fig. 1). Most of the UOG development is located across a six county region in north-central Arkansas, which we herein refer to as “the Fayetteville Shale”, meaning the geographic region of UOG development (as it is commonly referred in the literature) and not the geological formation (which covers a larger area). After the first unconventional well was drilled in 2004, drilling rates increased rapidly so that by 2017, there were 6239 wells established over an 11,000 km^2 area (Arkansas Oil and Gas Commission 2018). However, by 2017, drilling had stopped, production was in decline (over 40% from 2013 peak production, Energy Information Administration 2018a), and UOG companies had moved development activities to more economically valuable locations (e.g., Marcellus Shale). Therefore, the Fayetteville Shale is a location where reclamation of wells and subsequent recovery of ES could begin. The Fayetteville Shale is also a good model for the likely development scenarios of other shale basins in the United States and around the world because it is one of the oldest UOG regions, has already reached maturity, and has been relatively well-studied by the scientific community (see “Methods” section).

In this study, we wished to determine (1) the abandonment rate of wells in the Fayetteville Shale, (2) the amount of land available for reclamation, (3) the reclamation rates and costs, and (4) the ES value of reclaimed wells and the potential value of unreclaimed wells. We focused on three important ES values: agriculture, timber production, and climate regulation related to the carbon cycle. We chose these services because the region is an important agricultural and timber production area and the natural habitat present (temperate deciduous forest) is important to the global carbon cycle (Bonan 2008; NASS 2014). In addition, these three services have well-established methods of calculation. There are numerous additional ES values for all natural and semi-natural habitats (deGroot et al. 2002), but many of these values are difficult to estimate with precision (Fisher and Turner 2008). We anticipate that the estimation of ES values for agriculture, timber production, and climate regulation could inform citizens and policy makers about the value of investing in land reclamation where wells are no longer producing.

Methods

The Fayetteville Shale formation is located in north central Arkansas and was first developed for unconventional drilling in 2004. While this geologic formation covers a large area of Arkansas and small part of Oklahoma, most of the development has been focused in a six-county region of Arkansas (Fig. 1). As of 2017, a total of 6239 unconventional wells have been drilled (Arkansas Oil & Gas Commission 2018). Previous studies have described the various environmental impacts of this activity (Entrekin et al. 2011, 2018a, 2018b; Clark et al. 2013; Johnson et al. 2015; Moran et al. 2015, 2017; Peischl et al. 2015; Cox et al. 2017; Austin et al. 2018).

All well information was gathered from Enverus.com, an industry database that catalogs and updates all wells in the United States. We first downloaded well information from each of the six counties and sorted the data by status classification (as of 31 December 2017) and by year drilled. From these data, we plotted the number of wells drilled and abandoned per year (Table S1). We assumed that all wells classified as abandoned, plugged and abandoned, temporarily abandoned, and inactive were “dry” and would not produce natural gas in the future. While a status of “temporarily abandoned” would indicate potential future production, we found no evidence in the oil and gas database that our sampled wells were ever reopened after temporary abandonment. Most temporarily abandoned wells are later classified to one of the other non-producing categories listed above. Therefore, wells classified as such were included in our analysis.

For each county, we measured a random sample of wells that included ten of each non-producing category described above (inactive, plugged and abandoned, abandoned, or temporarily abandoned). For each well, we determined if the well was located on a pad that did not contain other producing wells (i.e., those classified as active, defined by Enverus.com as currently producing) as indicated by satellite imagery overlaid with well locations (Enverus 2017). If no active wells were located with this abandoned or inactive well, we concluded that the infrastructure was reclamation eligible. We then manually measured and classified the habitat impacted by well infrastructure by using satellite imagery (25 cm resolution) and the ruler tool in Google Earth Pro™. Historical imagery from Google Earth Pro was used to visualize the habitat prior to well development. We classified habitats as either natural forest, pasture, or plantation forest, which are land cover types that are easily identifiable in recent high-resolution satellite images. For more detailed description of these categories, see Moran et al. (2015). In our study region, over 90% of the landscape is composed of either natural forest (47%), pasture (38%), or plantation forest (6%).

We estimated values associated with three select ES: agricultural production, timber production, and climate regulation. We chose these three ES because there are reliable methods to quantify them with low uncertainty and data are available for our study region. These values also are commonly estimated in case studies of this biome (temperate deciduous forest, De Groot et al. 2012) and thus, we have high confidence in the calculations. The major food production ES in this region are from pastures which are utilized for cattle ranching, dairy farms, and hay production. The natural vegetation is temperate deciduous forest, which is known to be a valuable carbon sink and therefore important for climate regulation (Chazdon 2008). Timber production occurs in both natural forests and plantation forests. In the Fayetteville Shale region, natural forests are a mixture of oak (*Quercus* spp.), hickory (*Carya* spp.), and pine species (short-leaf pine, *Pinus echinata*), while plantation forests are typically maintained as single species landscapes of loblolly pine (*Pinus taeda*).

For agricultural production, we utilized the U.S.D.A. National Agricultural Statistical Services database that provides county-level agricultural production (i.e., sales value in USD) values (National Agriculture Statistics Service 2014). We suggest that total “sales” values are the best measure of all economic output derived from agricultural lands because they include the money farmers spend on agricultural activity and associated profits. For each county, we recorded the mean agricultural value per hectare for 2012, the most recent year of available data. We then assumed that all well pads that were located in pastureland (the dominant agricultural type in our study region) would have this agricultural value if not developed for unconventional gas production. Using the estimated number of reclamation eligible well pads, the average pasture-covered area of each pad, and the county-level agricultural production values, we calculated the total annual amount of agricultural production that was lost to unconventional gas development.

For timber production, we obtained county-level timber production values from Arkansas State Forestry Commission (Miles 2017). We utilized county-level 5-year averages (2011–2015) of timber harvest (both acreage and monetary value) for hardwood and softwood timber values and calculated the proportion of land harvested each year based on total acreage of natural forest and plantation forest. We then calculated the area of natural forest and plantation forest located on reclamation eligible well pads to determine the value of lost ES.

To estimate ES costs for climate regulation, we first estimated the carbon storage amounts for natural forest and pastures using values from Houghton (1999) and values from Liao et al. (2010) for plantation forests. These values include carbon stored in live biomass and soil. To determine the maximum recoverable carbon values, we multiplied each estimate by the amount of land in its respective habitat classification that was occupied by reclamation eligible wells. This amount of carbon was then multiplied by the "social costs of carbon", defined as the economic costs that each ton of carbon imposes upon society due to climate change impacts (Tol 2008). Because loss of live biomass due to development is one-time cost, we pro-rated the carbon value over 50 years for both forest types and 10 years for pasture land, since that is the estimated time to recover from disturbance (Houghton 1999).

Reclamation of agricultural land would also presumably increase the number of cattle, the predominant agricultural product in our study region. Other agricultural practices that produce methane (e.g., rice farming) are common in Arkansas, but not within the areas included in this study. We determined the mean number of cattle per hectare (NASS 2014) in our study region and assumed that this density of cattle would be established on restored pasture lands. We then estimated their annual methane production (55 kg/individual, Crutzen et al. 1986), the CO_2 equivalent of methane (which has 21 times the greenhouse gas impact, IPCC 2007), and the social costs (Tol 2008) of this production. These values were then included in our total valuation as a negative benefit. We assumed grazing is in equilibrium, in that carbon removed by grazing is equal to carbon fixed by plant growth over time.

In order to calculate the accumulated value of our three ES, we had to incorporate the "recovery time" for habitat to return to its original state. We utilized a 50-year time period for forested land and a 10-year time period for pasture lands, as estimated in Houghton (1999). We then utilized the Chapman–Richards equation stated below (Pienaar and Turnbull 1973) to model change in ES over time:

$$y_{(t)} = y_{(\max)}\left[1 - e^{-kt}\right]^{p},$$

where, $y =$ value of ecosystem service, $e =$ base of natural logarithm, $t =$ time (years), and k and p represent empirical growth parameters that scale absolute growth and shape the growth function, respectively. These parameters were identified for each biome in the available literature (Houghton 1999; Yan 2018; Table S2). The predictions of the model summed over 50 years represented the estimated ES values that could be achieved by reclaiming eligible well infrastructure. The Chapman–Richards equation is a commonly utilized model to simulate the growth of organisms, forest, or other objects that grow and approach a maximum asymptote (i.e., logarithmic growth).

Reclamation and subsequent restoration of landscapes back to their original condition has associated labor and material costs. There are no published values for reclamation costs of wells in the Fayetteville Shale of Arkansas nor for most geographic locations. However, we found four academic, government, and industry data sources that provided estimates of dirt work (e.g., pit filling, topography regrading), site preparation, and revegetation costs (Andersen and Coupal 2009; Dansby 2010; GAO-10-245 2010; Oklahoma Energy Resources Board 2018). We utilized the mean value of these estimates as our one-time reclamation cost. Together with the Chapman-Richards models, we then used these values to estimate the breakeven point in time when ES benefits exceed costs. We also plotted one standard deviation of the cost estimate to show a potential range of breakeven points.

We summed the ES costs calculated for agriculture, timber production, and climate regulation (and subtracted methane costs) to get the total ES costs of reclamation eligible wells in the Fayetteville Shale. Some well infrastructure had been reclaimed, which was determined through examination of historical and current satellite imagery. By estimating the number of wells that had been reclaimed, we determined the amount of ES that are in the process of being recovered, while the balance (i.e., unreclaimed wells) was calculated as annual ES losses available for reclamation. Based on well abandonment rates, we then estimated the future ES costs that we predict will be eventually be recoverable. All monetary values, which were obtained from a variety of sources described above, were inflation adjusted to 2017 USD.

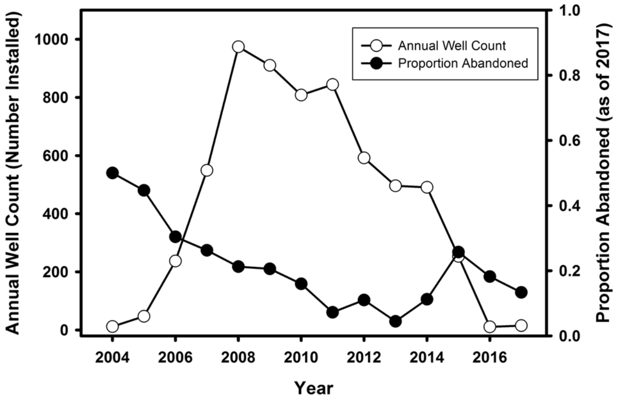

Fig. 2 Annual number of wells installed (open circles, left *y*-axis) and the proportion of wells drilled each year that were abandoned as of 2017 (closed circles, right *y*-axis)

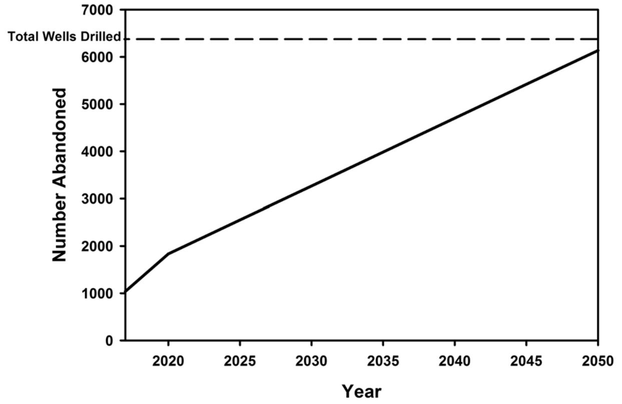

Fig. 3 Estimated number of wells that will be abandoned in the future assuming previous abandonment rates continue and no new wells are drilled

Table 1 Fayetteville Shale estimates of (**A**) the area of land developed by wells and corresponding annual costs in ecosystem services (ES), and (**B**) the area of reclamation eligible well sites (as of 2017) and corresponding maximized ES benefits

A		ES costs (USD 2017)	
Habitat	Developed area (ha)	Agricultural	Carbon
Natural forest	8048	77,502	1,565,062
Agricultural	4092	15,172,236	579,807
Methane emissions			−132,889
Plantation forest	207	1391	30,707
Total cost per service		15,251,129	2,042,687
Grand total			17,293,816

B		ES benefits (USD 2017)	
Habitat	Reclamation eligible area (Ha)	Agricultural	Carbon
Natural forest	218	2097	42,501
Agricultural	582	2,124,916	82,411
Methane emissions			−18,900
Plantation forest	54	363	8031
Total benefit per service		2,127,376	114,043
Grand total			2,241,419
Reclamation costs (one time)			6,769,180

Well sites that are “reclamation eligible” are defined as infrastructure that only supports nonproducing gas wells. Agricultural values include timber (natural forest and plantation forest habitat) and traditional agricultural production (e.g., livestock and crops for agricultural habitat)

Results

The number of wells drilled annually rose rapidly after 2004, peaking in 2008 (Fig. 2). After 2014, the number of new wells declined dramatically, reaching near zero by 2016. By 2017, the proportional number of wells abandoned was relatively high for wells drilled early in the Fayetteville Shale development (>25% for 2004–2007) and relatively low for those drilled later (13% for 2017). As expected, the age of the wells was a significant predictor of the proportion of wells that were non-producing (linear regression, $R^2 = 0.52$, Table S3A; both inverse and logistic models were poorer fits compared with the linear model). Logit transformation of the proportional well data also produced a poorer fit, so we retained the analysis of untransformed data. By the end of 2017, 1038 wells were non-producing, which was about 17% of the total drilled since development began.

From the linear regression equation generated from the well age versus abandonment rate ($y_i = 0.023x_i + 0.068 + e_i$), we were able to predict future abandonment rates (155 wells per year) and, assuming no additional wells are drilled, the year when most wells will be non-producing. By the year 2050, about 98% of all wells are predicted to be non-producing and presumably abandoned (Fig. 3). The abandonment that occurs over time will lead to ever increasing annual ES costs that would then be recoverable with active reclamation of well sites.

We estimated that the Fayetteville Shale development is costing the region about $17 million USD (2017) annually due to lost agriculture production, timber production, and carbon storage (Table 1). Agricultural production accounts for almost 95% of the total value (Fig. 4a, b). Since carbon values were calculated as a one-time benefit, the cumulative values reach an asymptote when the ecosystem fully sequesters the maximum amount of carbon (Fig. 4a). Conversely, agriculture presumably provides economic benefits in perpetuity, leading to a linear increase in total value over time (Fig. 4b). Total annual ES costs for reclamation eligible wells that have not been restored equal more than two million USD per year. Methane production by the predicted increase in cattle on restored lands (i.e., a negative benefit) was only 1% of the total ES values (about $18,000 USD per year at maximum, Fig. 4a). Total one-time reclamation costs were estimated at around $6.7 million (±2.8 million 1 SD), so total ES benefits would exceed costs in year three (2–4

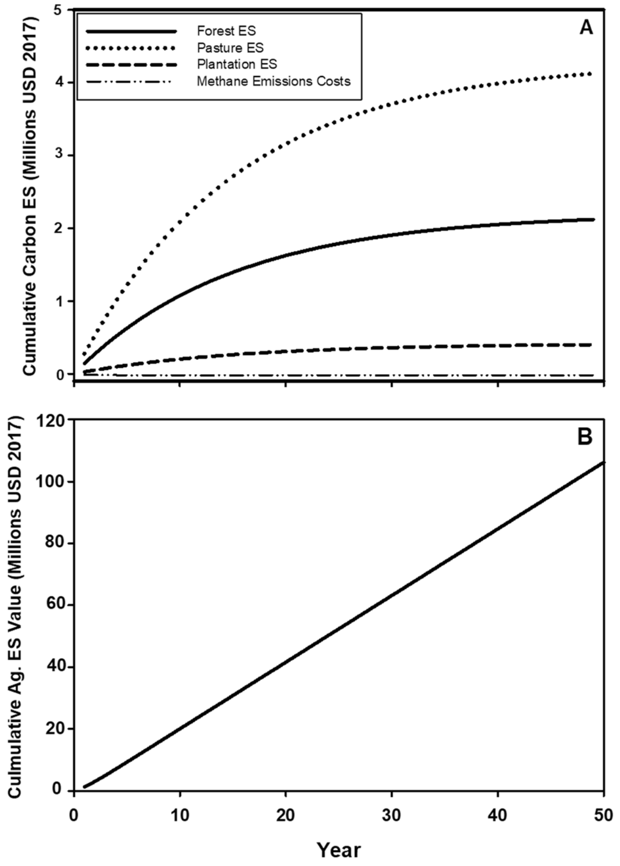

Fig. 4 Accumulated ecosystem services values for **a** carbon and **b** agricultural production over time for reclaimed lands (Chapman–Richards model calculations). Note that carbon sequestration is calculated as a one-time value (lifetime social costs, Tol 2008) so it reaches a maximum value when stored carbon is maximized for a given habitat. Since agricultural production is achieved each year (expressed in yearly sales), its value continues to increase indefinitely. Methane emissions are a negative value

years based on one standard deviation of mean estimate, Fig. 5). The lost agricultural production estimate is supported by the data on the change in agricultural sales between 2007 and 2012 in the Fayetteville Shale production region and surrounding counties, which showed a negative relationship between county well count (wells drilled during the 2007–2012 time period) and change in sales (linear regression, $R^2 = 0.33$, $y_i = -0.145x_i + 0.412 + e_i$, Fig. 6, Table S3B). Wells that have been actively reclaimed as of 2017 account for almost $600,000 USD in potential ES benefits, a sum that is almost entirely in agricultural value (Table 2).

Discussion

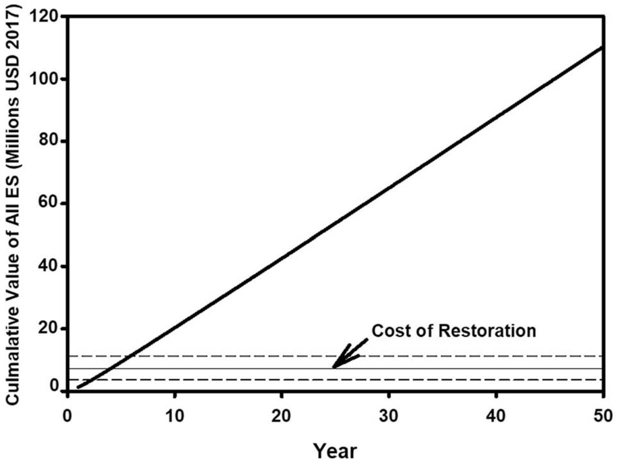

Fig. 5 Cumulative value of all three ES (including negative effects of methane emissions) and the estimated one-time cost of reclamation for eligible lands in the Fayetteville Shale of Arkansas. Estimated cost of reclamation is labeled, dashed lines indicate 1 SD of estimate

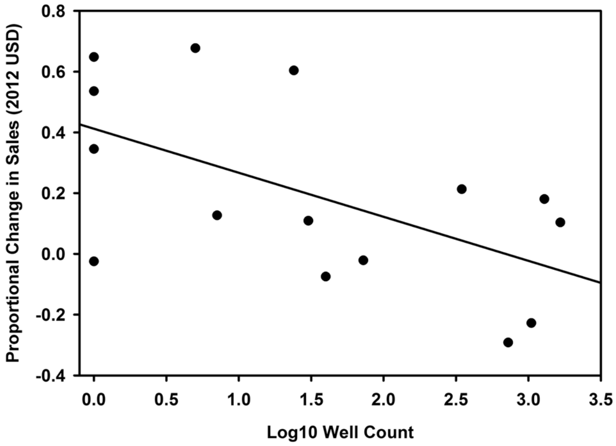

Fig. 6 County level well completion count (2007–2012) and county level proportion change in agricultural sales for the same time period

Table 2 Estimated annual ecosystem services (ES) benefits gained after full recovery from abandoned Fayetteville Shale wells that have been actively reclaimed as of 2017

		ES benefits (2017 USD)	
Habitat	Area reclaimed (ha)	Agricultural	Carbon
Natural forest	5	49	972
Agricultural	146	540,460	20,687
Methane emissions			−4741
Plantation forest	8	54	1187
Total value per service		540,563	18,105
Grand total			558,668
Reclamation costs (one time)			1,260,304

Almost one-fifth of the wells in the Fayetteville Shale are currently non-producing, and while the amount of reclamation eligible well infrastructure and the associated habitats are relatively small, we project that this amount will rapidly increase. Currently, many abandoned wells are located on well pads that still support other producing wells. By 2050, we predict that practically all wells will be abandoned and large amounts of land eligible for reclamation will likely be available. As seen in our calculations, this reclamation would result in the reestablishment of valuable ES. Our analysis assumes previous abandonment rates will be predictive of future rates and that no new wells will be drilled. We also assume that economic conditions of the past (e.g., gas prices, technological advancement, extraction costs, alternative fuel developments) will be similar in the future, although these variables are notoriously difficult to predict (e.g., gas prices fluctuate based on a host of economic conditions). Nevertheless, declining well production is a function of geology, so we have no reason to believe abandonment rates would be lower than predicted. Since drilling ceased in 2017, there are also no indications that drilling will return. Major gas companies (Chesapeake Energy, Southwestern Energy, and Billiton) have sold their stake in the Fayetteville Shale for the stated reasons of low profitability (Associated Press 2011; Brown 2018a, 2018b). This activity suggests that additional drilling will be uneconomical unless gas prices rise significantly or technological advancements increase production efficiency in this region (Ikonnikova et al. 2015).

We found that, as of 2017, only about 20% of reclamation eligible well pads and associated roads were reclaimed, despite the voluntary best practices recommendations for restoration to original landscape characteristics as soon as possible after abandonment (U.S. Fish and Wildlife Service 2007). We also found that over 90% of the reclaimed areas were restored to pasture (Table 2), even though about half of the original habitat developed was either natural forest or plantation forest (Fig. 7). We argue that lands should be reclaimed to their original habitat, as does the U.S. Fish and Wildlife Service (2007) in their best practices recommendations. In particular, restoring forested areas would reduce the effects of fragmentation. In the Fayetteville Shale, many large contiguous areas of forest were fragmented for well pad, road, and pipeline development (Moran et al. 2015). Since fragmentation of habitat often has profound negative effects on species (Ries et al. 2004), restoring land within forested areas could have wide-ranging conservation benefits, especially for those species that require large blocks of contiguous habitat (Manolis et al. 2002). In addition, temperate deciduous forest (the natural habitat in this region) is an important carbon sink and climate regulatory habitat (Bonan 2008).

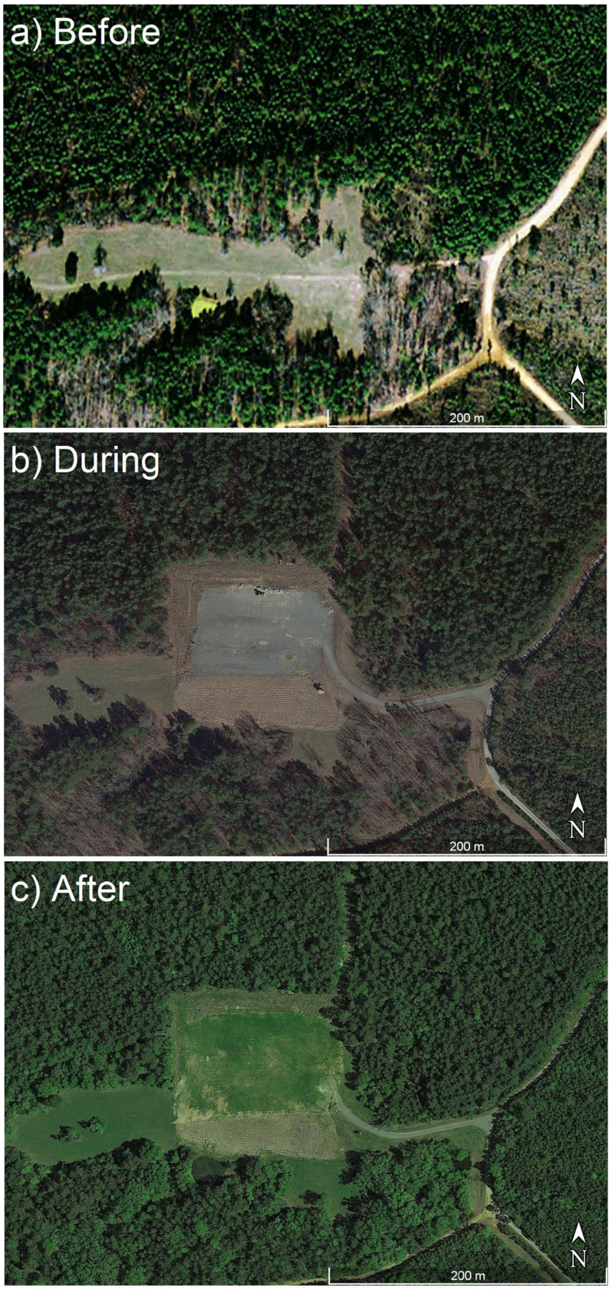

Fig. 7 Satellite imagery showing a landscape of natural forest and pasture **a** before development to a well pad (2006), **b** during operation of the well pad (2012), and **c** after "restoration" of the well pad to pasture (2016)

The federal government and individual states require the bonding of drilling sites to cover future plugging and land reclamation costs of sites disturbed by oil and gas drilling. However, the amount of money required for these bonds is often vastly smaller than the true reclamation costs (Boyd 2001; Mitchell and Casman 2011; Ho et al. 2018). The rates in Arkansas are "unspecified" (Davis 2015) but not to exceed $100,000, so it is unclear how much companies are devoting to this issue. Considering that plugging costs alone (not considered in our study) can exceed $100,000 for an unconventional gas well suggests that current bonding requirements do not meet the needs for land reclamation and restoration. Therefore, funds for reclamation will rely upon changing rules on bonding requirements, government spending, or incentive-based rules for landowners (e.g., tax deductions for land reclamation).

Our estimate of reclamation eligible lands is conservative since we only measured well pads and other structures directly associated with individual pads (e.g., access roads). As has been noted in other publications (Brittingham et al. 2014; Moran et al. 2015; Trainor et al. 2016; Howden et al. 2019), supporting infrastructure (e.g., compressor stations, pipelines) can be a substantial proportion of the land developed and modified during oil and gas exploration and development. However, unlike well pads and directly associated structures, supporting infrastructure is often shared by multiple wells and therefore it is impossible to distinguish active from inactive structures using satellite images. Presumably, as more wells are abandoned, comparable amounts of supporting infrastructure will be abandoned and the lands they occupy will become eligible for reclamation.

Oil and gas development tends to spread across large areas, even if only relatively small amounts of land are directly impacted. For example, in the 500,000 ha region where UOG development has occurred in the Fayetteville Shale, 10,000 ha have been directly developed or modified (Moran et al. 2015). Thus, the effects of direct land development may not be immediately apparent to the general public. Our results, however, show that the ES in agriculture, timber, and climate regulation are worth millions of dollars locally (agriculture) and globally (climate). Furthermore, as the number of active wells in the Fayetteville Shale declines, the cumulative costs continue to increase as the economic benefits decrease. Thus, a public education campaign might be valuable to increase awareness of the issue and develop public support for regulatory changes. The benefits of reclamation are both economic and environmental, which increases the probability of bipartisan support. The agricultural benefits should be especially efficacious as a way to communicate to the Arkansas public. Arkansas as a whole, including our rural study region, has a large number of farms and high rates of land ownership. These communities might be especially receptive to programs that improve agricultural output, and subsequently the value of private property. There would also be value in making land reclamation mandatory for oil and gas operators, which is currently voluntary (U.S. Fish and Wildlife Service 2007). However, this change in regulatory law would likely meet strong resistance from the fossil fuel industry.

The Fayetteville Shale was one of the earliest unconventional gas shales in the United States to be developed. Unconventional oil and gas development is now concentrated in other areas across the country, in particular the Permian Basin of Texas and New Mexico, and the Marcellus/Utica Shales of Pennsylvania and Ohio (Energy Information Administration 2018b, 2019). These areas, which cover larger geographic areas and have higher well counts, are likely to experience similar boom-bust cycles and leave behind a large amount of land to be reclaimed. Therefore, the Fayetteville Shale can serve as a model of the environmental and economic impacts of unconventional drilling and how to mitigate them.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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