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Declining human pressure and opportunities for rewilding in the steppes of Eurasia

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Abstract

Aim: Large and ecologically functioning steppe complexes have been lost historically across the globe, but recent land-use changes may allow the reversal of this trend in some regions. We aimed to develop and map indicators of changing human influence using satellite imagery and historical maps, and to use these indicators to identify areas for broad-scale steppe rewilding.

Location: Eurasian steppes of Kazakhstan.

Methods: We mapped decreasing human influence indicated by cropland abandonment, declining grazing pressure and rural outmigration in the steppes of northern Kazakhstan. We did this by processing ~5,500 Landsat scenes to map changes in cropland between 1990 and 2015, and by digitizing Soviet topographic maps and examining recent high-resolution satellite imagery to assess the degree of abandonment of >2,000 settlements and >1,300 livestock stations. We combined this information into a *human influence index* (HI), mapped changes in HI to highlight where rewilding might take place and assessed how this affected the connectivity of steppe habitat.

Results: Across our study area, about 6.2 million ha of cropland were abandoned (30.5%), 14% of all settlements were fully and 81% partly abandoned, and 76% of livestock stations were completely dismantled between 1990 and 2015, suggesting substantially decreasing human pressure across vast areas. This resulted in increased connectivity of steppe habitat.

Main conclusions: The steppes of Eurasia are experiencing massively declining human influence, suggesting large-scale passive rewilding is taking place. Many of these areas are now important for the connectivity of the wider steppe landscape and can provide habitat for endangered megafauna such as the critically endangered saiga antelope. Yet, this window of opportunity may soon close, as recultivation of abandoned cropland is gaining momentum. Our aggregate human influence index

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captures key components of rewilding and can help to devise strategies for fostering large, connected networks of protected areas in the steppe.

KEYWORDS
agricultural abandonment, ecological integrity, human pressure, Landsat, landscape connectivity, passive rewilding, steppe restoration

1 | INTRODUCTION

Temperate grasslands are among the Earth's most expansive biomes. Rich in biodiversity, they also provide important ecosystem services such as carbon storage (Dixon, Faber-Langendoen, Josse, Morrison, & Loucks, 2014). Many temperate grasslands are located on the most productive soils of the world and have therefore been widely converted to cropland and—where less productive—to pastures (Wright & Wimberly, 2013). As a result, the extent of natural grasslands in the temperate zone has declined strongly. In North America, only small and isolated natural prairie patches remain amid a matrix of cropland (Zilverberg et al., 2018). In Europe, not a single large complex of natural grasslands (i.e. grasslands that are subject to little or no deliberate direct modification by humans (Gibson, 2009)) remains that still exhibits interactions between large herbivores, fire and vegetation (Wesche et al., 2016). As a result, many grassland species have been declining and are now of conservation concern. Identifying grasslands of high nature conservation value and restoring natural grasslands across larger areas is therefore important (Fuhlendorf, Davis, Elmore, Goodman, & Hamilton, 2018).

Recent socioeconomic trends may provide opportunities for achieving this goal. Following structural changes and intensification in agriculture, marginal lands are being abandoned in many grassland regions globally (Estel et al., 2015; Mottet, Ladet, Coque, & Gibon, 2006). This, in turn, may allow the restoration of the ecological integrity of grasslands, particularly with regard to natural disturbance regimes (e.g. fire), increased connectivity of grassland patches and trophic complexity (e.g. large herbivores). All these components are key aspects for promoting the restoration of self-sustaining ecosystems (Du Toit & Pettorelli, 2019; Perino et al., 2019), in grasslands and generally, regardless of whether strategies to foster rewilding involve management (i.e. active rewilding) or follow a hands-off approach (i.e. passive rewilding (Martin, 2005; Svenning et al., 2016)).

The restoration of wildness in grasslands also often has a range of cascading positive effects for biodiversity (Corlett, 2016; Navarro & Pereira, 2012) and ecosystem services, particularly non-provisioning ones (Perino et al., 2019). For example, where agricultural land is abandoned and natural succession takes place, large amounts of carbon are sequestered (Griscom et al., 2017; Schierhorn et al., 2019; Vuichard, Ciais, Belelli, Smith, & Valentini, 2008), nutrient availability may recover (Rey Benayas, Martins, Nicolau, & Schulz, 2007), pollination services may increase (zu Ermgassen, McKenna, Gordon, & Willcock, 2018), and populations and habitats of plants and animals recover (Kamp, Urazaliev, Donald, & Hoelzel, 2011; Queiroz, Beilin, Folke, & Lindborg, 2014; Sieber et al., 2013). Given the current scarcity of natural grasslands in many regions, and the potential multiple benefits of restoring them, identifying places where steppe rewilding could take place is a conservation priority.

Both locating candidate areas for grassland rewilding and measuring rewilding progress remain challenging. In part, this is because rewilding research has often focused on forests (Jepson, 2016), and adequate tools and datasets for steppe regions are often missing. Furthermore, while the restoration potential of temperate grasslands has repeatedly been assessed, existing work has typically focused on small regions or individual sites within agricultural landscapes (Fuhlendorf et al., 2018). We are not aware of any assessment for rewilding opportunities at the broad scales needed to establish connected and self-regulating grassland complexes. Recently, considerable progress has been made in framing what such assessments could look like. Specifically, two fundamental dimensions need to be considered when identifying rewilding opportunities and progress: changes in human influence and changes in ecological integrity (Torres et al., 2018), where the latter can be framed to collectively capture changes in disturbance regimes, connectivity and trophic complexity (Perino et al., 2019). To our knowledge, no study has yet applied this framework to any grassland region of the world.

Identifying and mapping indicators capturing different aspects of rewilding can reveal priorities for conservation planning. For instance, protected areas in many grassland regions are typically sparse and isolated from each other (Saura, Bastin, Battistella, Mandrici, & Dubois, 2017; Saura et al., 2019). Passive rewilding might provide opportunities to enlarge protected areas, to expand protected area networks by adding new reserves or to establish corridors to restore and maintain connectivity between protected areas (Perino et al., 2019). Embedding protected areas in landscapes where human pressure is declining and rewilding is taking place is also important, as protected areas can contain source populations of conservation-dependent species (Wolf & Ripple, 2018). Such protected areas can serve as starting points for range recolonization where rewilding leads to increasing habitat availability and reduced human-induced mortality (e.g. due to hunting). It is therefore important to map indicators capturing key dimensions of rewilding and relate them to the spatial distribution of current protected areas and potential corridors linking these.

The Eurasian steppe is particularly interesting in the context of rewilding opportunities. This region, stretching from Eastern Europe to the Altai mountains, is situated nearly entirely within the former Soviet Union and contains the vast majority of Old World Steppe

(Wesche et al., 2016). Remnant populations of large grazers, such as the critically endangered saiga antelope (*Saiga tatarica*) or kulan (*Equus hemionus kulan*), still roam these steppes or have been recently reintroduced (Kock et al., 2018; Robinson, Milner-Gulland, & Alimaev, 2003). The region provides critical stopover habitat for Eurasia's migratory birds and hosts large populations of many species that are of high conservation concern in Western Europe (Kamp et al., 2016; Rounsevell, Fischer, Torre-Marin Rando, & Mader, 2018).

Across the Eurasian steppe, the extent and intensity of agriculture have both decreased substantially since the collapse of the Soviet Union in 1991 (Meyfroidt, Schierhorn, Prishchepov, Müller, & Kuemmerle, 2016; Schierhorn et al., 2016). As a result, many areas are now undergoing secondary succession (Beurs, Henebry, Owsley, & Sokolik, 2015; Brinkert, Hölzel, Sidorova, & Kamp, 2016). However, so far there has not been an assessment of the broad-scale spatial patterns of declining human influence in these steppes that would allow the formulation of rewilding visions. Kazakhstan has an ambitious programme to expand its protected areas system considerably, starting in 2010 (Kamp et al., 2015), so there is now a "hot moment" (sensu Radeloff et al., 2013) for conservation in Kazakhstan. At the same time, protected areas in Kazakhstan are typically very large, understaffed and underfunded. Identifying places where human influence is declining or low might therefore help to establish a manageable network of protected areas in the country (sensu Pringle, 2017).

Our overarching goal was to develop and map rewilding opportunities, using the Landsat archives to map post-Soviet land-use change across large areas (Dara et al., 2018; Yin et al., 2018), as well as high-resolution Google Earth imagery together with historical maps to monitor additional indicators of changes in human influence in steppes. Focusing on northern Kazakhstan and the period 1990–2015, we asked:

1. What were the patterns of post-Soviet changes in cropland area, livestock density and human population density across the steppe?
2. Where are the steppe areas that have seen declining human influence, which might therefore undergo passive rewilding?
3. How has declining human influence affected the connectivity among protected areas in the region?

2 | METHODS

2.1 | Study area

Our study region comprises three provinces in northern Kazakhstan (Kostanay, Akmola and North Kazakhstan oblasts), covering 38 million ha (Figure 1). The region extends across three ecoregions, namely forest steppe, steppe and semi-desert (Olson et al., 2001). The region has a rainfall gradient from 400 mm annually in the north to 200 mm in the south. The climate is continental with average temperatures of 22°C in July and −18°C in February (Afonin, Greene, Dzyubenko, & Frolov, 2008).

The natural vegetation comprises grasslands dominated by tussock grasses (genera *Stipa*, *Festuca* and *Koeleria*) and wormwood (genus *Artemisia*) (Lavrenko & Karamysheva, 1993). While *Artemisia* increases in cover towards the dryer south (Brinkert et al., 2016), the northern steppes are largely characterized by mesophytic herbs. Across the ecotonal forest steppe, there is a mosaic of herb-rich meadows and forest patches composed of birch (*Betula pendula*) and Scots pine (*Pinus silvestris*). Historically, the overall ecological conditions across the steppe belt have been remarkably stable across the past 18,000 years (Tarasov et al., 1998, 2000). During the last glacial maximum, steppe was already the dominant vegetation type across the wider region and steppes also occupied a much larger area in the European and southern Siberian parts of Eurasia, extending further north than today (Tarasov et al., 2000). From the early Holocene onwards, birch and pine spread northwards and formed the forest steppe ecotone found in northern Kazakhstan today (Tarasov, Jolly, & Kaplan, 1997). Generally, the distribution of steppe and forest patches is driven by soil factors and disturbance such as fire and

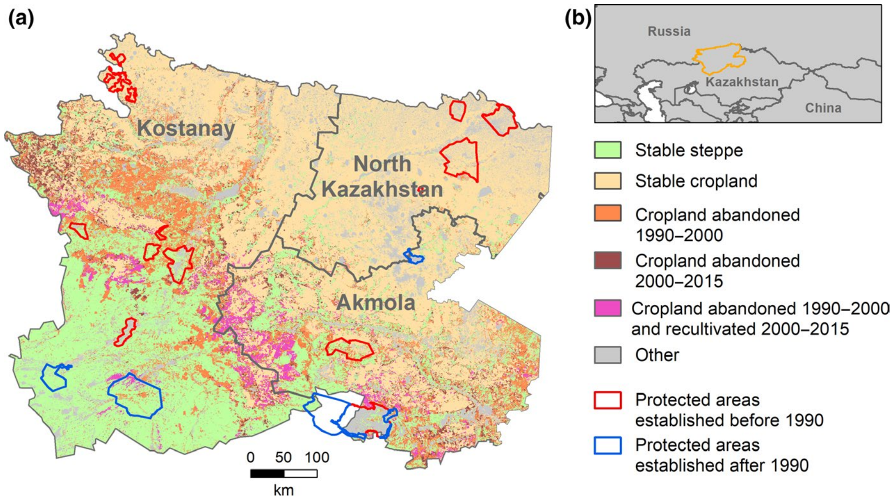

FIGURE 1 (a) Cropland dynamics in the study area, mapped from Landsat images. (b) Location of our study area in north-central Kazakhstan

grazing. The steppe belt is a “brown black region,” in which grazing and fire are the main consumers of biomass (Bond, 2005).

Megafauna has been an integral component of steppe ecosystems over long time periods. During the Pleistocene, woolly mammoth (*Mammuthus primigenius*), woolly rhinoceros (*Coelodonta antiquitatis*) and steppe bison (*Bison priscus*) roamed the steppe belt (Stuart, 1991), but these species went extinct in the early Holocene (Sandom, Faurby, Sandel, & Svenning, 2014). A few grazers, such as horse (*Equus ferus*), kulan (*Equus hemionus*), saiga antelope, auroch (*Bos primigenius*) and red deer (*Cervus elaphus*), persisted until the late Holocene (Chibilyov, 2002; Pushkina & Raia, 2008). From the mid-Holocene onwards, increasing human pressure through hunting and livestock negatively impacted remaining megafauna (Hanks, 2010; Schieltz & Rubenstein, 2016), and by the end of the 19th century, all large herbivores had been hunted to extinction except for small remnant populations of saiga antelopes (Milner-Gulland et al., 2001).

Historically, nomadic pastoralism was the main land use across the Eurasian steppe. The first signs of horse domestication date back to the Botai culture in northern Kazakhstan 5.500 BP. Nomadic pastoralism developed around 3.200 BP (Hanks, 2010), involving movements between the more productive steppes in the north that were grazed in summer and the southern, more arid steppe with dwarf shrub vegetation and little snow cover that were grazed in winter. This form of pastoralism persisted until the 1930s, when nomads were largely forced into a sedentary lifestyle by the Soviet rulers (Robinson et al., 2003). Later on, between 1954 and 1963, over 5 Mha of Kazakh steppes was converted to croplands during the Soviet “Virgin Lands Campaign” (Kraemer et al., 2015), and livestock numbers increased strongly again, primarily in form of large state farms (Yan et al., 2020). After 1991, as a result of institutional change, diminishing support for agriculture and large-scale human outmigration (Lesiv et al., 2018; Schierhorn et al., 2013), at least 48 million ha of cropland was abandoned across Russia and Kazakhstan alone (Lesiv et al., 2018). In Kazakhstan, grazing livestock numbers decreased by as much as 70% (Lioubimtseva & Henebry, 2012; Schierhorn et al., 2016), while remaining livestock were increasingly concentrated around larger settlements (Hankerson et al., 2019; Kamp et al., 2015).

2.2 | Mapping changes in cropland extent

To map changes in cropland extent, we generated Landsat image composites for the years ca. 1990 (i.e. the end of the Soviet era), ca. 2000 (first decade of the transition period, and the period when land-use intensity decreased heavily) and ca. 2015 (current situation, after a partial revival of the agricultural sector). Image composites are gap- and cloud-free mosaics based on Landsat images (Griffiths, Jakimow, & Hostert, 2018). For each of the three time steps, we calculated three composites centred on spring (Julian day 121), summer (day 180) and fall (day 260) to capture phenology differences that are important for mapping cropland-grassland dynamics (Baumann et al., 2011). We also calculated a set of spectral–temporal metrics for which we considered all available cloud-free observations for each year.

We gathered training data through on-screen digitization of high-resolution images in Google Earth, visual examination of the Landsat composites and land-use information collected in the field (see Dara et al. (2018) for details). We then classified our Landsat image composites using random forests, a nonparametric machine-learning technique (Breiman, 2001). Finally, we applied a minimum mapping unit of 10 Landsat pixels (equal to 0.9 ha) and validated the resulting land-cover map using 100 randomly sampled points per class, following best-practice protocols (Olofsson et al., 2014). Our land-cover change map had an overall accuracy of 86.3% (for details on the accuracy assessment, see Text-S1 and Table SI-1).

2.3 | Mapping changes in human population density and livestock distribution

We used human population and livestock numbers as proxies for overall human influence on steppes. To map human influence, we assessed changes in the extent and condition of settlements and livestock stations from the Soviet period until today. Livestock stations in the study area are outposts where livestock are concentrated in summer (“*Letovki*”) or winter (“*Zimovki*”). These stations usually consist of up to three houses or tents (“*yurts*”) for shepherd accommodation, stables and corrals. To assess changes in settlement and livestock station density, we digitized both for circa 1984 (representing infrastructure in the Soviet period) and circa 2012 (representing the current situation). For the Soviet period, we manually digitized settlements and livestock stations across the study region from georeferenced, declassified Soviet military topographic maps scaled 1:200,000 and labelled them as “fully intact” assuming that abandonment did not start prior to 1991, in-line with estimates of livestock numbers which declined only after 1990 in Kazakhstan (Robinson & Milner-Gulland, 2003). For the current situation, we used publicly available, high-resolution satellite images (2.5-m resolution or higher) in Google Earth and Bing Maps (for details see Koshkina et al., 2019), to determine the level of intactness of settlements and livestock stations (10% intact, 20% intact, etc.; see Text-S2 for further information).

2.4 | Changes in human influence across the steppe

Using our maps of cropland extent, grazing stations and settlements, we mapped changes in human influence (Carver, Comber, McMorran, & Nutter, 2012) from 1990 to 2015. We generated three layers with a common spatial resolution (300 m; 10 × 10 pixels in our Landsat-based land-cover map) that contained (a) the share of cropland per grid cell, (b) the distance to settlements and (c) the distance to livestock stations. We scaled the values from 0 to 1 such that higher values represented higher human influence (e.g. areas near active livestock stations and settlements). Next, we combined these three layers into a "human influence index," comparing two alternatives: (a) the product of the three layers (assuming overall pressure is the combined impact of these pressures) and (b) the average of the three layers (i.e. assuming additivity of pressures; see Appendix S1). This index assumes that lower human influence is beneficial from a passive rewilding perspective. Last, we calculated changes in our human influence indices from 1990 to 2015, which captures the extent to which areas are might undergo passive rewilding—ranging from 0 (low) to 1 (high).

2.5 | Changes in landscape connectivity

To determine how changes in human influence impacted connectivity, we assessed landscape connectivity across our study region using circuit theory (McRae & Kavanagh, 2012). Circuit theory describes the movement of individuals through a landscape by considering all possible pathways between grid cells of a resistance surface (i.e. our maps of human influence). Each pathway can be interpreted as a current. Grid cells that are part of many pathways thus have a higher current density compared to grid cells that are part of fewer pathways. The cumulative current density map of all pathways can be interpreted as overall landscape connectivity (Koen, Bowman, Sadowski, & Walpole, 2014). We applied the CircuitScape algorithm (Shah & McRae, 2008), which calculates the current between nodes. The nature of the algorithm causes the highest current densities to be found around these nodes (Koen et al., 2014; McRae, Dickson, Keitt, & Shah, 2008). In the context of predicting functional connectivity across a larger region, this can result in biased results, particularly if distances between some nodes are small. We avoided this problem by randomly placing nodes within a buffer region outside our study area, and we followed Koen et al. (2014) and Leonard et al. (2017) to find the best combination of (a) the buffer width around our study region and (b) the number of nodes within the buffer, by subsequently increasing the number of points and buffer widths. For each combination, we calculated current density maps and compared them to previous maps (i.e. with less points and a smaller buffer) using Pearson's *r*. We stopped increasing buffer width and number of nodes when our current density map did not change compared to the previous map, and we defined this as when *r* exceeded .98. The final buffer width was 50% of the study region extent, and the final number of nodes in that buffer was 60. Based on this parameter combination, we built current density maps for 1990 and 2015, and calculated the difference between the two maps (for more details on the connectivity analyses, see Text-S3).

2.6 | Rewilding effects on protected area connectivity

We compared changes in our human influence index to the network of protected areas and assessed the location of protected areas relative to areas of higher landscape connectivity. In addition, we evaluated how older (i.e. established prior to 1990) and newer (i.e. established after 1990) protected areas are located in our study region. In July 2018, there were 44 officially registered protected areas in Kazakhstan, covering about 24.9 million ha (i.e. 9% of the country area). Protected areas in Kazakhstan are categorized as follows: Strict State Nature Reserves ("Zapovedniki," IUCN category Ia) are wilderness areas with no permitted use except research. National parks (IUCN category II) are specially protected areas of historical, cultural or natural value used for scientific research and recreation and are subdivided into four zones. Reserves ("Rezervaty," IUCN category Ib or II) are areas for sustainable use of local resources with a focus on nature conservation. Finally, local reserves ("Zakazniki," IUCN category IV) are smaller protected areas with a zoological, botanical or geological focus where land use is restricted but allowed.

3 | RESULTS

3.1 | Cropland change

Our satellite-based assessment showed widespread cropland abandonment (Figure 1). From the estimated ~20.3 million ha under crops in 1990, nearly 6.2 million ha had been abandoned by 2015 (i.e. a decrease in used cropland of 30.5%). Most cropland abandonment in the region occurred between 1990 and 2000 (28.0% of all cropland in 1990 abandoned, 5.7 million ha). While 17.1% of these areas were recultivated during the following period, cropland abandonment continued to be the dominant land-use change in the study area (1.49 million ha, 10.2% of all cropland in 2000, Figure 2).

The extent of abandoned cropland varied substantially across the three provinces, with high rates in Kostanay (40.2% abandoned, equalling 3.6 million ha) and Akmola (33.3%, 2.4 million ha), but a much lower rate in North Kazakhstan (3.7%, 0.15 million ha, Figure 2). From 1990 to 2000, cropland area contracted the most in Kostanay (3.1 million ha or 35.5%), followed by Akmola (2.4 million ha or 32.4%) and North Kazakhstan (0.12 million ha, 3.1%), and we found much lower rates during 2000–2015 (Akmola 12.0% (0.59 million ha), Kostanay 14.9% (0.86 million ha) and North Kazakhstan 0.7% (0.03 million ha) (Figure 2). Recultivation of cropland (0.96 million ha in total, 17.0% of all cropland abandoned until 2000) was highest in Akmola (0.52 million ha, 22%) and Kostanay (0.44 million ha, 13.8%) while almost nonexistent in North Kazakhstan (0.004 million ha, 3.2%).

The number of settlements also decreased substantially between 1990 and 2015 (Figure 2). Across the entire study area, 14% of all settlements were completely abandoned, 81% were partly abandoned (i.e. with at least 10% of all buildings demolished), and only 5% of all settlements remained intact or increased in size (Figure 2). Regarding livestock stations, abandonment rates were even higher, with 83% of all summer stations and 90% of all winter stations completely abandoned (i.e. no signs of use in ca. 2012), and an additional 16% of all summer stations and 7% of all winter stations

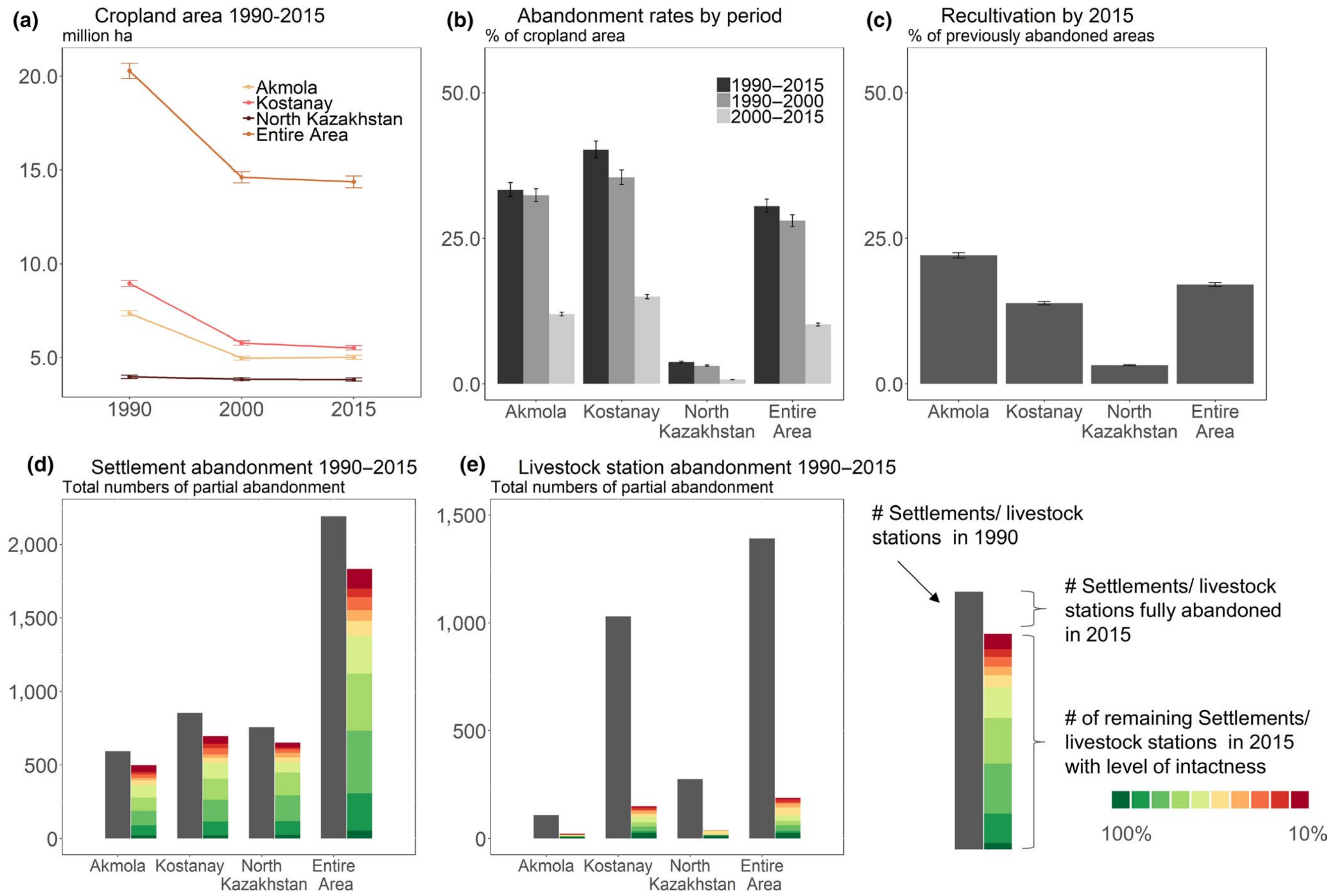

FIGURE 2 (a) Extent of cropland in the study area between 1990 and 2015. (b) Cropland abandonment per province and for the entire study area. (c) Recultivation of cropland in 2000–2015 of areas abandoned in 1990–2000. Error bars in a–c represent 95% confidence intervals in area estimates. (d and e) Settlement and livestock station abandonment in 1990–2015

at least partially dismantled. Only 1% of all summer and 3% of all winter stations used during Soviet times were still in use in 2015. We did not find any new livestock stations, nor stations that were larger now than they had been during Soviet times (Figure 2).

3.2 | Declining human influence on steppes

The post-Soviet trends of contraction in cropland, outmigration of the rural population and decline in livestock stations during the 1990s and 2000s resulted in massively decreased human influence on Kazakhstan's steppes (Figure 3). Combining our three spatial indicators (cropland change, settlement change, livestock station change) into an aggregated human influence index suggested substantial variation in human influence across our landscape. The pattern emerged independently of the chosen layer combination (i.e. product vs. sum), although the product showed stronger contrast in values as it is more sensitive to individual low values in one of the three layers (compare Figure SI-5). Human influence during Soviet times was lowest in southern Kostanay, where livestock grazing was the dominant land use. Across North Kazakhstan, Akmola and northern Kostanay, cropland was more abundant, generally resulting in higher human influence. After 1990, human influence generally decreased across the region. The decrease was strongest in Kostanay, whereas North Kazakhstan did not show a noticeable decline in human influence.

Assessing human influence in relation to the network of protected areas in our study region highlighted that the level of human influence inside protected areas decreased substantially between 1990 and 2015. As expected, in nearly all protected areas human influence values decreased regardless of protection level (i.e. IUCN categories I–VI, Figure 3). Before 1990, only protected areas in IUCN categories I and IV existed in the region, and category I protected areas showed lower human influence values than category IV areas, except for Tounsor and Sarykopa Zakazniks. Since 1990, four new protected areas were established (one each of categories I and II, and two of category VI), which were placed in regions of relatively low and decreasing human influence (Figure 3).

3.3 | Changes in connectivity

The changes in human influence also resulted in marked changes in landscape connectivity. Landscape connectivity mostly increased in Kostanay, whereas in North Kazakhstan and Akmola such changes were not widespread (Figure 4). Relative to protected areas, decreasing human influence resulted in increased connectivity

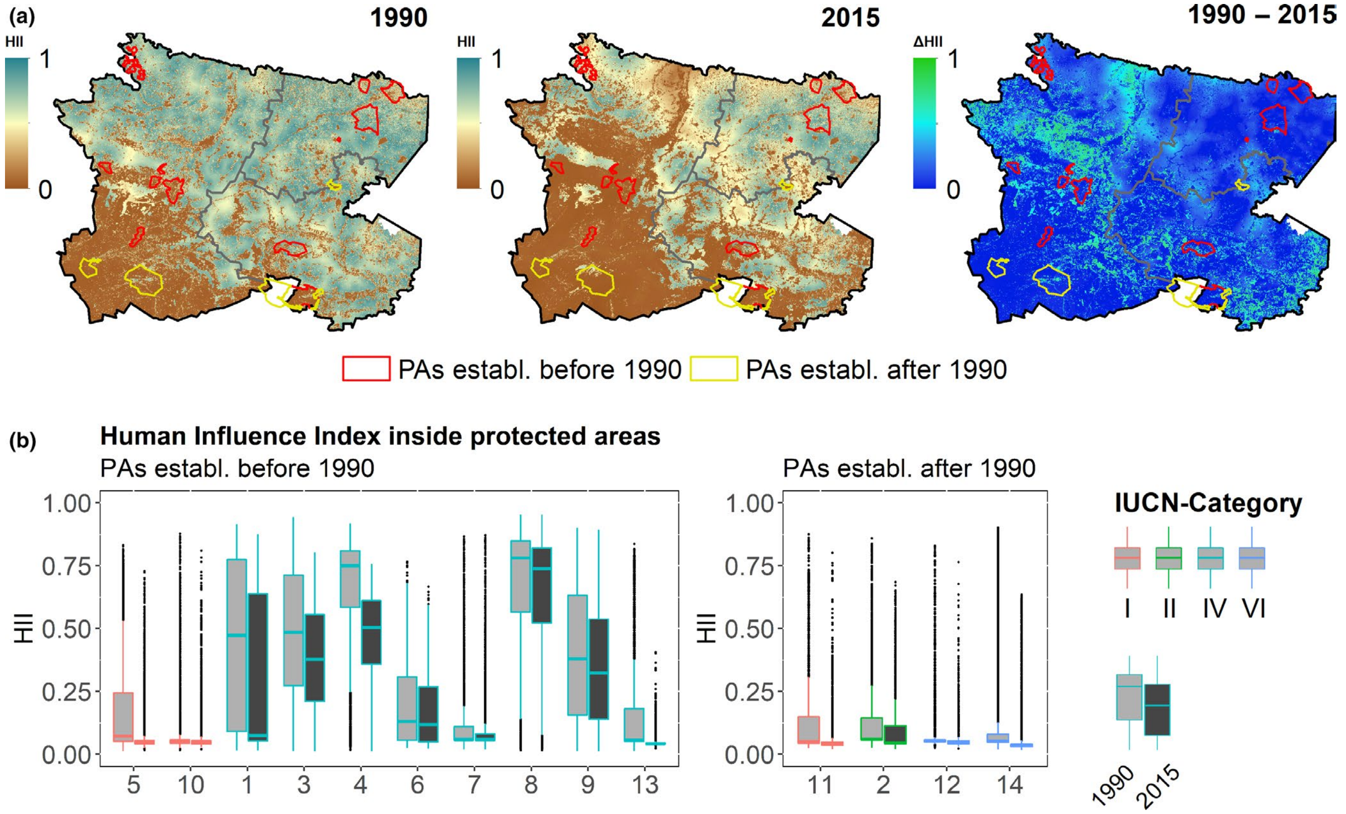

FIGURE 3 (a) Human influence index 1990 and 2015 as well as changes therein for our study area (we here show human influence calculated as is the product of the three input layers). (b) Human influence index within the protected area network. A list with full names of the protected areas and their location is provided in the Appendix S1

between older protected areas in central and southern Kostanay, and southern Akmola. Likewise, new protected areas (i.e. protected areas established after 1990) in these two regions were generally in areas of higher connectivity. Landscape connectivity also increased between protected areas in central Kostanay (i.e. between Naurzum Zapovednik, Tounsor and Sarykopa Zakazniks, Figure 4). Finally, some areas we found to have high landscape connectivity were facing cropland recultivation, particularly on the border between Kostanay and Akmola (Figure 4b).

4 | DISCUSSION

The world's temperate grasslands have historically been transformed due to land-use change on a large scale. Rewilding large grassland complexes that are characterized by natural disturbances, high connectivity and trophic complexity, and that thus foster the interactions between fire and native grazers that have shaped grasslands for millennia, is a bold conservation vision (Fuhlendorf et al., 2018). Post-Soviet changes in land use may provide opportunities for turning such visions into reality across the Eurasian steppe, which contains some of the largest remaining stretches of temperate grasslands in the world. However, adequate spatial data for identifying where human pressure has declined were missing. It was hence unclear where passive rewilding might currently take place or where restoration interventions, such as reintroducing large native grazers, could take place.

Focusing on a 38 million ha region of the Eurasian steppe in Kazakhstan, we used a novel approach to map an aggregate measure of changes in human influence, based on changes in cropland extent, grazing pressure and human population density. Our study provides three main novel insights. First, our analyses highlight a massive decline in human influence following the collapse of the Soviet Union in 1991, with more than 6 million ha of cropland abandoned. In addition, we detected that 97% of livestock grazing stations and more than 90% of settlements were substantially reduced in size or completely dismantled. This major decline in human influence suggests substantial potential for restoration and conservation. Second, our analyses highlight that areas of ongoing passive rewilding have the potential to link existing protected areas. Protected areas in our study are sparse and isolated, and recent trends can help establish a protected area network that benefits a wider array of species, such as large ungulates (Figure 4b), and natural processes, such as grazing–vegetation–fire interactions, than are currently protected. Finally, while our study highlights major conservation potential, the window of opportunity for implementing such broad scale protected area networks, and bold rewilding visions more broadly, may soon close. This is because recultivation of abandoned cropland is gaining momentum, Kazakhstan's population is growing (Kamp et al., 2016), and foreign investment is increasingly directed at natural resources

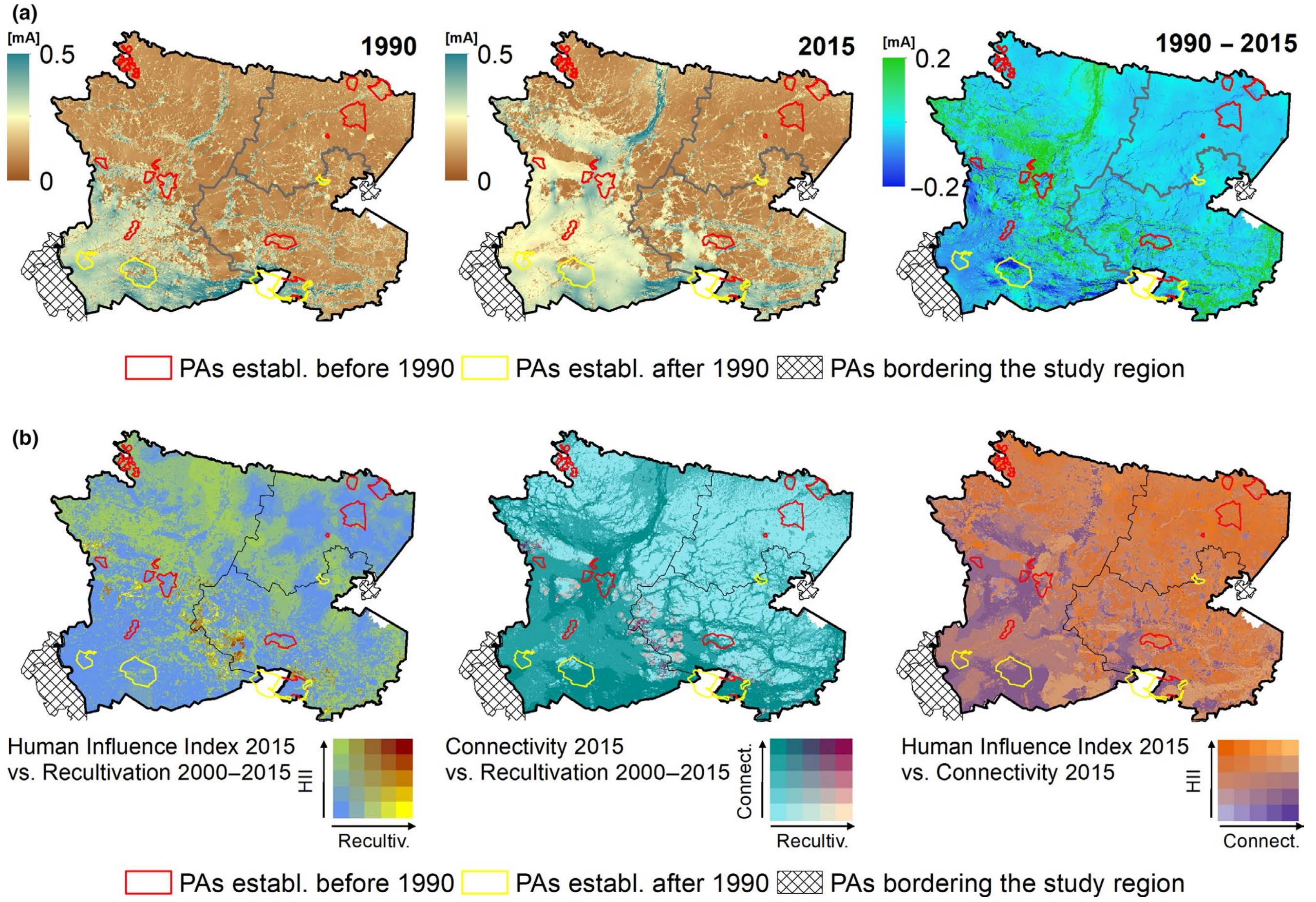

FIGURE 4 (a) Changes in landscape connectivity between 1990 and 2015. (b) Human influence index (left) and connectivity (middle) in relation to recultivation pressure (Recultivation pressure refers to areas which were abandoned 1990–2000 and then recultivated in 2000–2015); human influence index 2015 versus Connectivity 2015 (right)

across the Kazakh steppe (e.g. via China's new silk road initiative (Fallon, 2015)).

Cropland abandonment and outmigration of the rural human population happened across the former Soviet Union, but here we show that human influence declined particularly strongly in the steppes of Kazakhstan. Across the former Soviet Union, cropland abandonment was high in European Russia, Belarus and Ukraine (Prishchepov, Radeloff, Dubinin, & Alcantara, 2012; Schierhorn et al., 2013), with abandonment rates of over 40%, and the cropland abandonment rates we document for northern Kazakhstan were similarly high (over 40% in Kostanay). Importantly though, ours is the first study that quantifies the additional, massive decline in grazing pressure—for any steppe region in the former Soviet Union—with an area footprint many times larger than that of cropland abandonment (Figure 3). In the case of north-central Kazakhstan, the main drivers of these trends were large-scale human outmigration (Meyfroidt et al., 2016), the transition from state to market-driven economies (Rozelle & Swinnen, 2004), which made crop production unprofitable, as well as the collapse of state-owned farms. While agricultural sectors rebounded to some extent after 2000, many of the land-use changes that have happened since 1991 are likely to persist, for example because Soviet-era agriculture expanded onto marginal areas, or because infrastructure has been dismantled since 1991. Croplands have been partly recultivated, as we show here, but a redistribution of grazing stocks to abandoned regions has not yet been detected (Hankerson et al., 2019). Northern Kazakhstan should therefore be a priority region for active or passive rewilding with the goal to restore steppes.

Our analyses capture changes in human influence, one of two core dimensions along which to assess progress towards rewilding (Torres et al., 2018). While we did not directly measure all components of ecological integrity recently suggested as pivotal (Perino et al., 2019), three lines of evidence suggest that many of the areas highlighted in our maps are indeed undergoing passive rewilding. First, regarding connectivity, our analyses highlight that declining human influence might have resulted in increased landscape connectivity among steppe patches, as well as among protected areas (Figure 3). This increased connectivity should immediately benefit the movements of large grazers such as saiga antelope, which can now roam over larger areas with less human disturbance—a key factor influencing their distribution (Singh & Milner-Gulland, 2011). In time, increasing connectivity of steppe habitat can also help grassland species that have suffered from conversion over long periods and might now rebound and expand their range towards their original extent, such as the endemic Bobak marmot (*Marmota bobac*) (Munteanu et al., 2020). Likewise, increased connectivity of steppe areas will allow plants and animals with low dispersal ability to recolonize regions where they are extinct due to historical steppe conversion, such as endemic tulip species (*Tulipa* spp., (Brinkert et al., 2016)).

Second, regarding natural disturbance regimes, it is now well documented that declining human pressure in the area has been accompanied by dramatic changes in fire regimes, with a general increase in fire frequency and severity (Dara et al., 2019), as elsewhere in the former Soviet Union (Dubinin, Luschekina, & Radeloff, 2011). Third, regarding trophic complexity, large mammals throughout the former Soviet Union have rebounded from high poaching rates in the 1990s, including wild grazer populations (Bragina et al., 2015), and several trophic rewilding initiatives are now underway to bring native grazers back to the steppe areas they disappeared from historically (Kock et al., 2018). Nevertheless, the massive decline in domestic livestock suggests many steppes may now suffer from undergrazing (Hankerson et al., 2019), which might be one of the main drivers of intensifying fire regimes due to fuel accumulation (Dara et al., 2019). Higher fire frequency leads to a decrease in fire-sensitive species and an increase in grass, a potential feedback loop that could be broken through ramping up active rewilding (i.e. the restoration of wild grazer populations such as Kulan).

In addition to these changes along the three dimensions of ecological integrity relevant for rewilding as proposed by Perino et al. (2019), declining human influence has also affected a wide range of ecosystem processes. For instance, cropland abandonment has increased soil carbon pools (Meyfroidt et al., 2016; Wertebach et al., 2017), and fire regimes have intensified substantially (Dara et al., 2019). Declining human influence has also markedly affected biodiversity, such as bird diversity which is recovering (Kamp et al., 2011), as well as plant community composition and species richness (Kämpf, Mathar, Kuzmin, Hölzel, & Kiehl, 2016) on abandoned croplands. Altogether, this suggests that our analyses indeed pinpoint areas where passive rewilding takes place, and our indices are useful for measuring progress towards more functional, self-regulating and complex ecosystems (Perino et al., 2019; Torres et al., 2018).

Our indices capture key dimensions of declining human impact and are widely applicable given the increasing availability of high-resolution satellite imagery, both current (e.g. Sentinel-II, Planet, imagery accessible in Google Earth or Bing) and historical (e.g. Landsat archives, aerial photographs, Corona imagery). Likewise, the historical maps we used are available across the entire Eurasian steppe, and similar maps are available elsewhere. Our work thus also underlines the value of making historical maps, here used to identify Soviet-era livestock stations, available in order to better understand historical human pressure. Similarly, historical aerial photographs or Corona imagery could be a powerful data source to track signs of human influence over time. It is important to note that our index represents a start but could be easily expanded to cover other aspects of human pressure (e.g. road infrastructure, land-use intensity, hunting pressure) once additional data become available. Likewise, our index could be integrated with a composite measure of ecological integrity, measuring for instance fire dynamics (e.g. Dara et al., 2019), steppe connectivity (Figure 3) and the observed or modelled distribution of keystone species (e.g. saiga, Figure SI-8), in order to measure progress towards increasing ecological integrity (Torres et al., 2018).

Our analyses also highlight key areas currently likely undergoing passive rewilding that may represent target areas for extending the region's protected area network. Existing protected areas are far from each other, as many of them were formed primarily to protect stopover sites for migratory birds (Schweizer, Ayé, Kashkarov, & Roth, 2014). Most of them are also not strictly protected (though our analyses suggest low human influence inside them; Figure 3). Expanding the existing protection area network seems particularly useful in the southern part of our study region, where the protection of relatively small areas would provide large benefits in terms of connectivity, while at the same time protecting critical saiga calving grounds (Figure SI-8) (Singh, Grachev, Bekenov, & Milner-Gulland, 2010). Integrating our human influence indices and connectivity analyses with distribution data for species of conservation concern would allow the identification of those areas and corridors that would maximize benefit for biodiversity (e.g. through allowing existing populations to occupy historic home ranges), while restoring functional steppes.

However, the window of opportunity to establish such a protected area network may be closing. While human pressure has declined drastically across the region, our analyses show that recultivation of previously abandoned areas is occurring in parts of the study area. While cropland has still not reached the Soviet extent, recultivation trends are worrisome from a conservation perspective, as recultivated areas appear to coincide spatially with areas highlighted in our analyses as important connectors between protected areas, as well as with key areas of saiga ranges (Figure SI-8). Reviving the agricultural sector, both in terms of higher crop production and an expansion of the livestock sector, is explicit goal of Kazakhstan's development of the agro-industrial sector (Ministry of Agriculture of the Republic of Kazakhstan, 2018). At the same time, Kazakhstan also is actively expanding its protected area network (Kamp et al., 2015). Conservation and land-use planning that seek to balance conflicts of both goals in areas particularly valuable for rewilding are therefore needed. This study provides insights on where such areas may be located, for both identifying areas particularly useful for conservation and rewilding (e.g. areas with low human pressure and high connectivity), as well as to identify areas where agricultural development would harm conservation opportunities less (Figure 4b, right).

At a time when human pressure is increasing in most world regions, making use of rewilding opportunities as they emerge is critical. Grasslands are among the most imperiled biomes of the world (Fuhlendorf et al., 2018), and the substantially reduced human pressure in the Eurasian steppe after the breakdown of the Soviet Union provides major opportunities for broad-scale steppe restoration. Our analyses highlight how a range of human influence indicators can be combined to provide a detailed and multidimensional picture of where and why human pressure declines, and where possible rewilding has been taking place, across large areas. This should provide a basis for conservation and land-use planning that makes use of opportunities to establish large, connected habitat complexes in the Eurasian steppe.

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DATA AVAILABILITY STATEMENT

All maps are available via Humboldt-Universität zu Berlin's cloud storage system (HU-Box) under the link: https://box.hu-berlin.de/f/76115576c5624468bcdc.

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BIOSKETCH

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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