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Recognizing Gilgai Microrelief in the State

R. M. Joeckel and L. M. Howard

ABSTRACT—This article details gilgai microrelief—a conspicuous pattern of repetitive small mounds or low ridges ("ups") and intervening depressions ("downs")—for the first time in Nebraska. Gilgai microrelief is a dynamic natural phenomenon that contributes to the diversity of local and regional landscapes while influencing soil processes, surface hydrology, plant communities, and land use. Scores of sites on soils atop the Pierre Shale in far northern Dawes and Sioux Counties exhibit mostly linear gilgai microrelief consisting of ridgelike microhighs and troughlike microlows that trend perpendicular to slope. Areas of linear gilgai microrelief are as large as 17.5 ha and individual ridgelike microhighs extend as long as 700 m. Linear gilgai microrelief exists chiefly on "washboard" ridges on shale, that is, parallel, elongated, strongly oriented ridges with west–northwest to north–northwest azimuths. Small areas (2.6 ha or less) of normal and lattice gilgai microrelief exist on some narrow ridge crests and summits in direct association with linear gilgai microrelief. Some wider, level summits exhibit small-scale reticulate patterning and subangular polygons (1.5 to 3.0 m in width) of uncertain origins. Our observations suggest that gilgai microrelief in the study area has been compromised by cattle tracks and soil erosion. Gilgai microrelief was likely more prominent prior to intense grazing.

Key Words: gilgai, microrelief, Pierre Shale, vertic soil properties

Introduction

Soil scientists define microrelief as "local, slight irregularities in [the] form and height of a land surface . . . too small to delineate on a topographic or soils map" (Soil Science Society of America, n.d.). Microrelief has multiple, disparate origins, but each of its forms reveals important details about the development of landscapes and soils atop it. The term "gilgai" refers to multiple remarkable forms of microrelief that have similar genetic origins (e.g., Hallsworth et al. 1955; Beckmann et al. 1971; National Committee on Soil and Terrain 2009, 129–30). To many soil scientists and geographers, gilgai is certainly the most conspicuous form of microrelief. It consists of alternating microlows and microhighs, typically of 1 m or less in amplitude, that form distinctive and even demonstrably regular (e.g., Milne et al. 2010) patterns on particular land surfaces. The etymology of the term lies in Aboriginal Australian dialect and its usage in pedological literature in that country became common after papers by Jensen (1911) and Prescott (1931).

Gilgai was repeatedly observed in association with particular soil types in diverse parts of the world throughout the 20th century, and the term gradually came into worldwide use. Gilgai forms on clayey soils, particularly those containing abundant smectite-group clay minerals, which swell and heave with wetting and contract and crack deeply with drying (Wilding and Tessier 1988; Mermut et al. 1996). The Upper Cretaceous Pierre Shale, which is the bedrock in a large part of Nebraska north of the Pine Ridge in Dawes and Sioux Counties (Fig. 1), is an example of a parent material of smectitic clayey soils in the US Great Plains. Soils developed on smectitic clayey materials that also have characteristic soil structures and features are classified as Vertisols in the United States and some other nations, and as Vertosols or "cracking clays" in Australia (McKenzie et al. 2004; Soil Survey Staff 2014; Khitrov 2016). There are also vertic intergrades within other soil orders in Soil Taxonomy, and such soils share some physical behaviors

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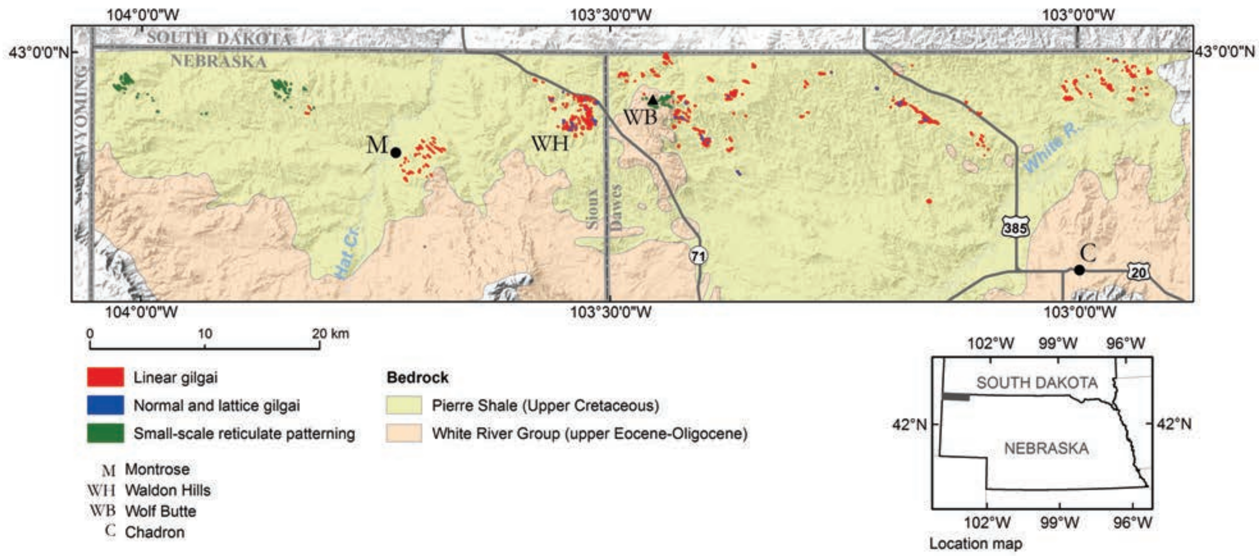

Figure 1. Map of study area. Geologic map data are from Conservation and Survey Division, School of Natural Resources, University of Nebraska–Lincoln.

and characteristics, such as comparatively high linear extensibility, deep cracks, and even microscopic features (e.g., Blokhuis et al. 1990; Soil Survey Staff 2014). Gilgai need not be present for a soil to be classified as a Vertisol (Soil Survey Staff 2014), but there is an overwhelming association between gilgai, where it exists, and Vertisols.

Gilgai microrelief's signal effect of small-scale but widespread patterning of the land surface into microhighs and microlows has demonstrable environmental impacts that even extend to the maintenance of biological diversity. Many important soil properties—such as soil-horizon and soil-profile thicknesses, depth of leaching and occurrence of secondary carbonates, water movement and episodic surface ponding, depth and timing of cracking, pH, exchangeable bases, and total nitrogen and organic-carbon contents—can differ between microhighs and microlows (Wilding et al. 2002). Gilgai microlows and microhighs likewise influence the density of vegetation (e.g., denser in microlows), partition plant species (e.g., xerophytes on microhighs and mesophytes in microlows) and encourage distinctive plant communities (Williams 1955; Warren Wilson and Leigh 1964; Russell et al. 1967; Verster et al. 1973; Thompson and Beckmann 1982; Wilding et al. 1990; Wondzell et al. 1990; Goudie et al. 1992, Weitkamp et al. 1996; Kovda et al. 1999). Gilgai is known to have significant negative impacts on the built environment including roads and building foundations (e.g., Gustavson 1975), as are the swelling, heaving, and cracking properties of Vertisols in general (e.g., Mathewson et al. 1975). The phenomenon even may have limited the spread of certain premodern agricultural practices (Duffield 1970).

Gilgai can be obliterated by cultivation, and in many places it probably has been, but it is also a dynamic phenomenon and it can form again *de novo* on agricultural landscapes within years to decades (e.g., Hallsworth et al. 1955; Hallsworth and Beckmann 1969; Blackburn 1974; Williams et al. 1996). Probable relict gilgai, which is now buried by other soil materials and cannot be related to active soil processes, has also been recognized in locales far from the present study area (Kabala et al. 2015; Diaz et al. 2016).

This article documents gilgai for the first time in Nebraska, albeit in a small area near the South Dakota line (Fig. 1). Gilgai is already known from a few parts of the Great Plains and Central Lowland in the interior of North America, but it has not been particularly well documented. For example, it has long been known that Vertisols exist atop the clayey, smectitic Pierre Shale in South Dakota, even though there are very few published studies of it (e.g., White and Bonestell 1960; White and Agnew 1968). Tanner (1958) and Ruppert (2017) provided figures of linear gilgai in Oklahoma. A recent article identified rare Vertisols and other soils with vertic properties in eastern Kansas, but it did not identify gilgai (Hartley et al. 2014). Vertisols have been mapped in certain parts of Minnesota, North Dakota, Manitoba, and

Saskatchewan (Mermut et al. 1996; Brierly et al. 2011), although not necessarily in conjunction with gilgai at the land surface. The discovery of gilgai in Nebraska broadens what remains, unfortunately, an incomplete understanding of the state's diverse physical landscapes and it opens avenues for future pedological, geomorphological, and ecological research in the study area.

Methods

Gilgai can be identified in aerial imagery by virtue of the specific patterns that it manifests. It is difficult to confuse gilgai with any other natural phenomenon, although other forms of non-periglacial, microtopographic ground patterning, such as mima mounds (e.g., Gabet et al. 2014) and the earthworm-generated mounds known as *surales* (Zangerlé et al. 2016), are generally similar in morphology but not in scale, spacing, and soil-landscape associations. Some terminology for gilgai that was once merely vernacular has been officially adopted and codified in Australia to describe specific morphological types of gilgai. Thus, crabhole, normal, linear, lattice, melonhole, and contour gilgai are recognized (Paton 1974; National Committee on Soil and Terrain 2009). Although some authors have advocated that only a few basic types of gilgai exist (Paton 1974), were gilgai to be fully characterized according to shape and orientation, many classes of the phenomenon might well be distinguished (e.g., Verger 1964; Khitrov 2016). Certainly, other descriptors have been applied to gilgai in the past, such as "high," "low," "network," "nuram," "tank," "tiger-stripe," "wavy," and others (Verger 1964; White and Agnew 1968; White 1970; Beckmann et al. 1971; Paton 1974).

The recognition of well-developed gilgai in aerial imagery is extremely straightforward if that imagery is of sufficient spatial resolution, and this maxim unequivocally applies in the present study. American geologist W. F. Tanner (1958) drew attention to the distinctive "fingerprint" pattern visible in aerial photographs of parts of Oklahoma and Texas, which Australian geologist K. A. W. Crook (1958) seems to have immediately recognized as linear gilgai directly related to processes in particular kinds of soils. Tanner (1958) may not have understood the pedological significance of his observations in terms of soil processes, but the regularly spaced and gently curving, ridgelike microhighs of linear gilgai is distinctive, even if it is only vaguely reminiscent of the ridges in a human fingerprint. Beckmann et al. (1973) recognized that, although linear gilgai typically trends parallel to the maximum slope on the shoulder-to-footslopes of hills, distinctly different types of gilgai predominate in other slope positions.

More than 300 separate geographic occurrences of gilgai and associated ground patterning (Fig. 1) have been identified north of 42.5°N latitude in northern Sioux and Dawes Counties in Nebraska through the examination of high-resolution aerial imagery from the years 1994 to 2014 in Google™ Earth Pro. The best resolution of these features is in imagery dated 2006 and thereafter, and imagery dated 2013 and 2014 proved exceedingly useful in identifying gilgai. In fact, overall, it is likely that gilgai would have gone unidentified if these very recent images had not been available. All gilgai described herein was discernible in Google® Earth Pro only at eye altitudes of less than 2,500 m, but it was most readily discerned at eye altitudes of only 1,300 to 1,500 m. Areas of gilgai were delineated in Google™ Earth Pro and then mapped in ArcMap® geographic information systems (GIS) software.

Results

Geography and Geology of Study Area

The observations of the regional landscape of northwestern Nebraska that emerged from this study are a starting point for the discussion of gilgai. A distinctive pattern of terrain eroded from the Pierre Shale dominates the small part of Nebraska that lies north of the Pine Ridge escarpment and its northern pediment slopes. This pattern is produced by numerous parallel, elongate ridges and the intervening valleys of ephemeral drainages, which themselves effect an overall pattern of subparallel to parallel, and frequently pinnate, networks (Fig. 2). Overall, such terrain is suggestive of an old-fashioned washboard having long, parallel ridges of corrugated metal, and so we apply that term hereafter as a descriptor. Washboard terrain in Nebraska extends from approximately 16 km north–northeast of Chadron westward to the area named Waldon Hills in easternmost Sioux County, (31 km north–northwest of Crawford), and thence westward across northern Sioux County (Fig. 1). Washboard terrain on the Pierre Shale extends even farther westward beyond the Nebraska line to the Seaman Hills in eastern Niobrara County,

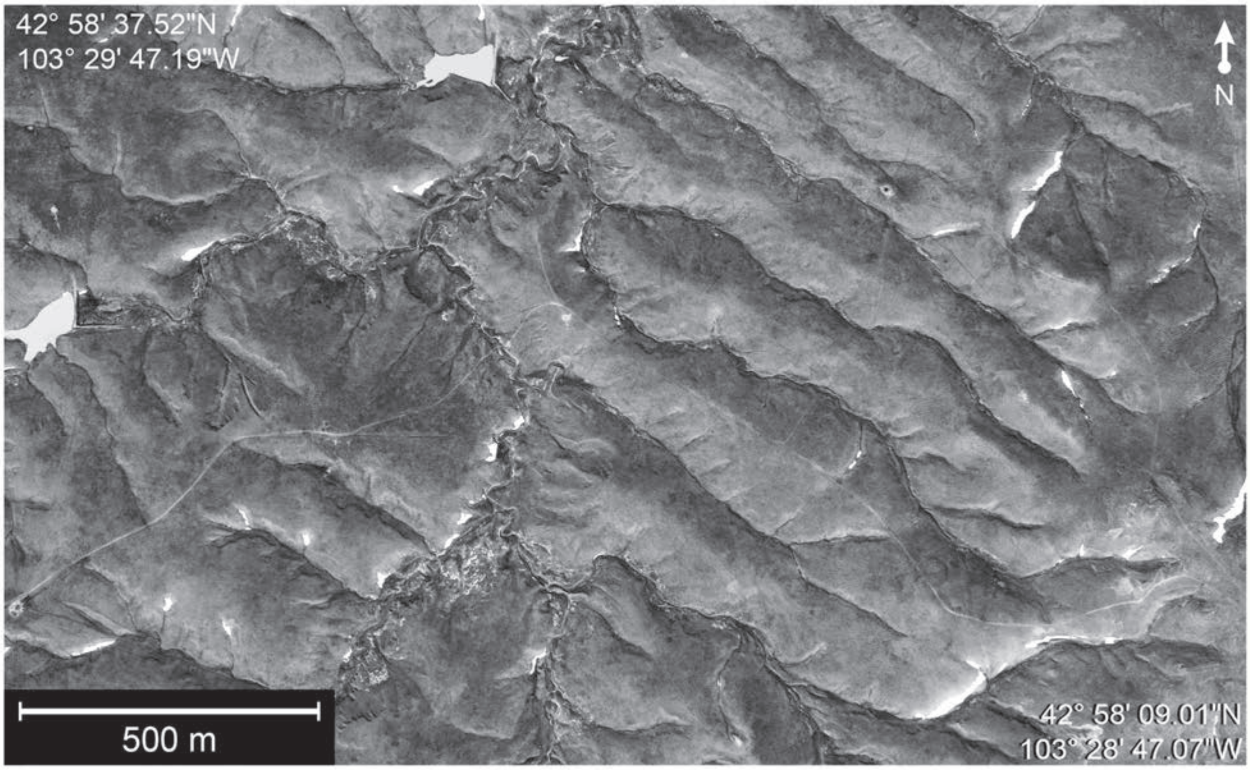

Figure 2. Typical washboard terrain on the Pierre Shale, as described in text, in northwestern Dawes County, Nebraska. Note strong NW–SE orientation of ridge crests and low-order streams in intervening valleys.

Wyoming, and northward to northeastward, many tens of kilometers into South Dakota.

Local relief in washboard terrain is approximately 35 to 60 m. Individual ridges in washboard terrain are approximately 50 to 700 m in width and typically 4.5 km or less in length. The basal widths of ridges range from 50 to 800 m, but most of the ridges are 120 to 300 m in width. Nevertheless, gilgai-bearing ridge crests and level summits are narrow—typically 50 m or less in width—in northern Dawes County and adjacent northeastern Sioux County. Gilgai-bearing ridge crests are wider in western Sioux County. Ridgelines are strongly oriented west–northwest to north–northwest along azimuths of 295° to 325°.

In contrast to the dominance of washboard terrain, there are few large areas of nearly level terrain (25 m or less of relief and slopes generally of 20% or less) in the study area. Wolf Butte, which lies in northwestern Dawes County nearly due north of Crawford (Fig. 1) is the most prominent of these areas. This steep-sided but nearly flat-topped 3.6-km-wide table is underlain by Pierre Shale, but it is also at least partially covered with the younger sedimentary strata of the White River Group.

Pierre Shale landscapes in far northwestern Nebraska and adjacent parts of Wyoming and South Dakota have multiple distinguishing characteristics that make them unique in comparison with surrounding areas. These characteristics include, but are not limited to, the commonness and mode of mass wasting (in particular, landslides), the nature of runoff and the attributes of drainage networks, and sodicity (amount of exchangeable sodium) of some of the constituent soils.

Characteristics of Gilgai in the Study Area

The overwhelming majority of gilgai described in this article can be classified as *linear* gilgai, or very long, parallel ridgelike microhighs with intervening troughlike microlows. Downslope-elongate microhighs and microlows in linear gilgai curve gently as they follow the elevation contours of slopes (White 1970; Beckmann et al. 1973, fig. 1; Verster et al. 1973, fig. 1). In addition to linear gilgai, there are other, less common types of gilgai in the present study area. Linear gilgai (Figs. 3–5) is found on the side, nose slopes, and (more rarely) head

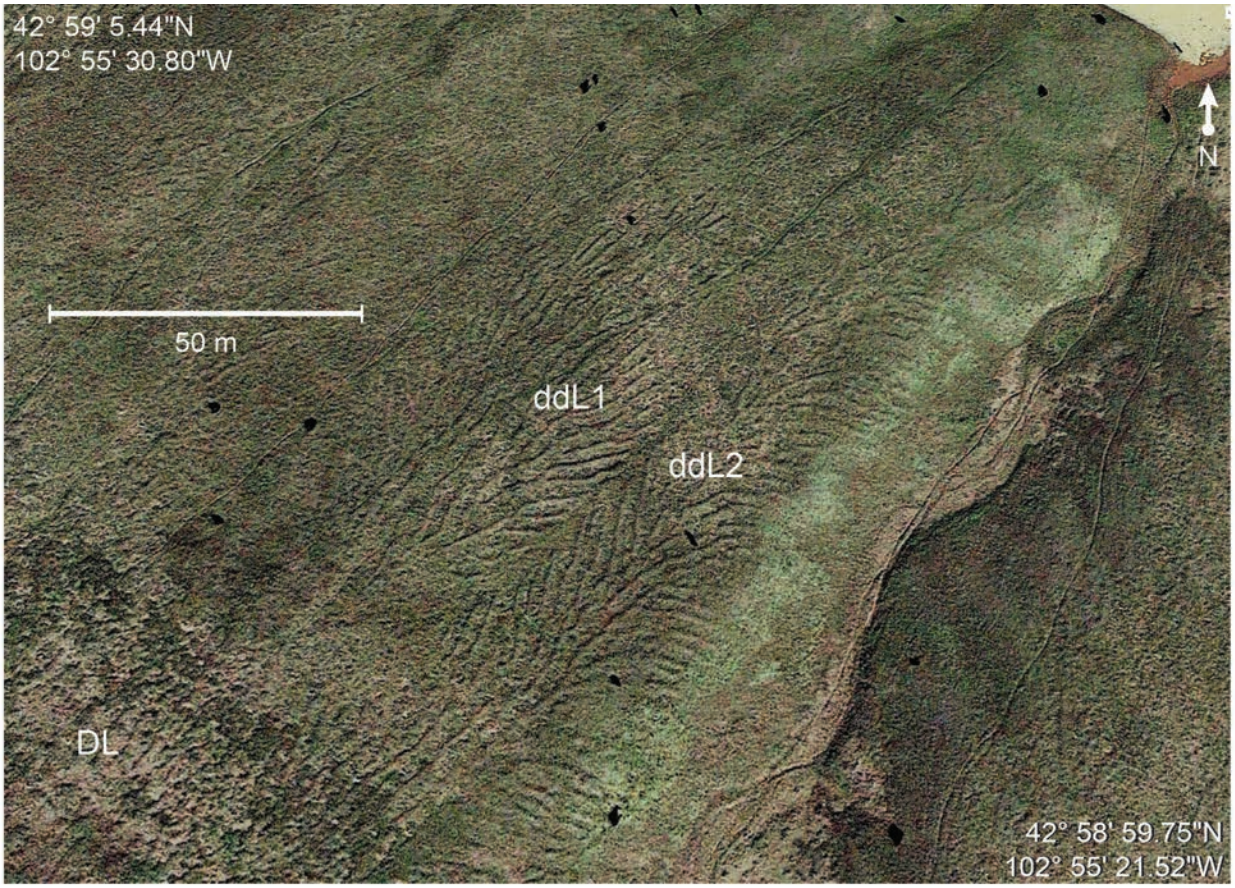

Figure 3. Well-developed, prominent linear gilgai on Pierre Shale ridgelines descending toward the upper right (ddL1, ddL2), Dawes County, 18 km NNE of Chadron, Nebraska. Downslope-diverging ridgelike microhighs effect a simple plumose pattern. Upslope, some linear gilgai has been degraded by erosion (DL). Google™ Earth Pro image dated October 15, 2013.

slopes of some ridges in washboard terrain (Figs. 3, 4), on slopes as steep as 70%. Most ridges in washboard terrain, however, exhibit no gilgai at all. In Dawes County, linear gilgai is most common north of the White River and northeast to north–northwest of Chadron (Fig. 1). Scattered linear gilgai can be found from there westward to the Sioux County line, including some on the flanks of Wolf Butte. In Sioux County, linear gilgai is common on ridges in the Waldon Hills and on the northwestern flanks of Stony Hill, immediately east of the unincorporated community of Montrose and southeast of Hat Creek, 33 to 37 km northwest of Crawford (Fig. 1).

Well-defined linear gilgai can be traced continuously over areas as great as 17.5 ha, although most sites cover much smaller areas. Separate large areas of well-defined gilgai, however, can exist in very close proximity, within 0.5 km or less of each other. The ridgelike microhighs in linear gilgai are approximately 20 m to 250 m in length and 0.7 to 4 m in width (most are 1 to 2.5 m in width). On the side slopes of washboard ridges, the long axes of ridgelike microhighs trend perpendicular to elevation contours and extend downward onto footslopes. Such examples are the very longest of linear gilgai microhighs in the study area. Many ridgelike microhighs in linear gilgai widen, at least slightly, downslope. The nose slopes of ridges in washboard terrain show a more complicated pattern of ridgelike microhighs. On nose slopes, shorter ridgelike microhighs curve gently and converge upslope at angles of 3° to 30°, usually merging with a single, longer, and commonly straighter ridgelike microhigh that extends upward toward the hill summit. (Reversely, Beckmann et al. [1973] described the same phenomenon as bifurcating downhill.) If the axis of the local ridge crest is extended downslope to imaginarily bisect the nose slope, then gently curved, somewhat comblike or plumose patterns of ridgelike microhighs exist on either side of that axis as rough mirror images (Figs. 3, 4). The crests of washboard ridges themselves

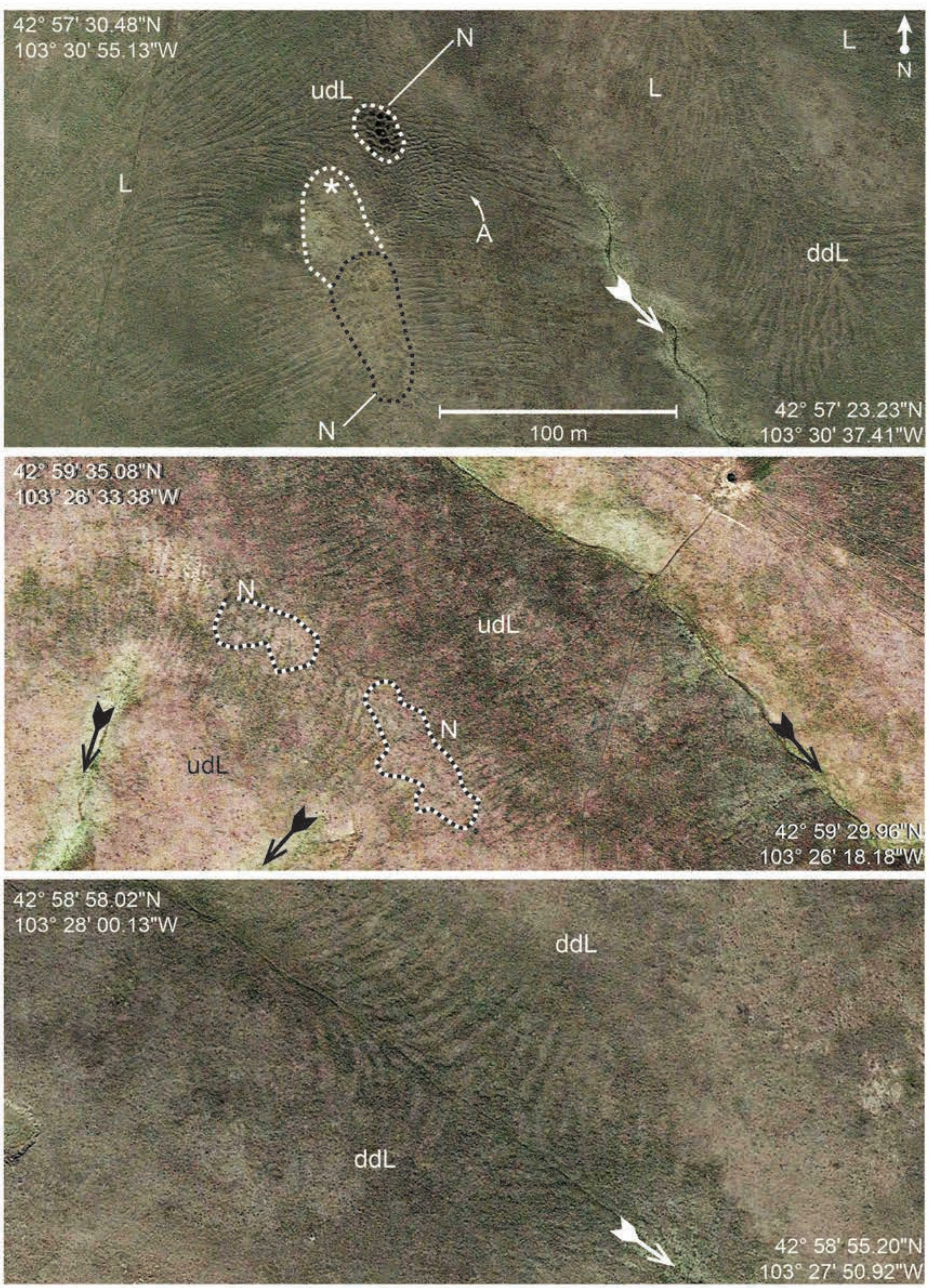

Figure 4. **Top**: well-developed linear (L, ddL, udL), normal (N), and lattice (A) gilgai in close association in Waldon Hills, Sioux County, approximately 43 km WNW of Chadron, Nebraska. Both upslope-diverging (udL) and downslope-diverging (ddL) ridgelike microhighs are visible. Normal (N) and lattice (A) gilgai are in close association at a narrow summit (complete white dashed outline). Part of another summit (incomplete white dashed outline with asterisk) exhibits some degree of surface patterning but seems to lack normal gilgai altogether or to have a very subdued expression of it. Arrow with head and tail represents direction of drainage in this and other images. Google™ Earth Pro image dated October 15, 2013. **Middle**: Linear gilgai on side slopes of a washboard ridge, diverging upslope toward the ridgecrest (udL) from both sides. Some normal gilgai (N) is present at ridge crest. Google™ Earth Pro image dated October 15, 2013. **Bottom**: Linear gilgai with downslope-diverging ridgelike microhighs (ddL) that nearly meet at drainage rill descending to lower right (arrow). Google™ Earth Pro image dated October 15, 2013.

Figure 5. **Top**: Spectacular complex of gilgai in washboard terrain, including associated lattice and normal (AN), normal (N), linear (L), and linear with upslope-diverging ridgelike microhighs in northwestern Dawes County, 35 km WNW of Chadron, Nebraska. Two depressions (1, 2) are episodically filled with water and both show the complex manifestation of gilgai sometimes referred to as "depression gilgai" (e.g., Young 1976, 188). **Bottom**: Close-up of basin 2 showing downslope-elongated "grain" of gilgai around depression (dashed line) characteristic of "depression gilgai" and also microrelief on desiccated basin floor (dark), which may be small-scale gilgai forming there. Note nearby normal gilgai (N) depressions. All from Google™ Earth Pro image dated September 21, 2011.

Figure 6. **Top**: Small-scale reticulate patterning of unknown origin on margins of Wolf Butte, Dawes County, Nebraska (see Fig. 1). See text for discussion. Google™ Earth Pro image October 15, 2013. **Bottom**: Large-scale normal gilgai on Burleson clay, a Vertisol (Udic Haplustert), 19 km NNW of Lake Ray Hubbard Dam, Wylie, Texas, shown at the same scale as the features on Wolf Butte in Nebraska. Gilgai depressions are darker because of their higher moisture content and are reticulate. The lighter pattern seen fringing the microlows is produced by connected, narrow microhighs. From Google™ Earth Pro image dated April 27, 2016.

widen slightly toward a narrow, flattish summit. Many of these summits are smooth in appearance, but some of them exhibit unique gilgai patterns of their own. Ridgelike microhighs on side slopes may also diverge *upslope* as they approach summits in some places, but less extensively so than the downslope-diverging ridgelike microhighs on nose slopes.

Normal and lattice gilgai, and the coexisting phenomenon of small-scale reticulate patterning (Fig. 6, top), are overall rarer than linear gilgai in the study area. In the present study area, there are very few clear-cut examples of normal and lattice gilgai (e.g., Beckmann et al. 1973; National Committee on Soil and Terrain 2009). These types of gilgai exist only in particular settings in which the land surface approaches level. Normal and lattice gilgai exist in close spatial association within areas of as much as 2.6 ha (Figs. 4, 5). Where two sets of long, ridgelike microhighs diverge upslope from opposite sides and meet at the shoulder-to-crest or on the ascending ridge crest of a washboard ridge, both sets break up into a complex pattern of much less elongate (2.5 to 10 m in length) microhighs, as if the two sets of diverging, ridgelike microhighs were physically interfering with each other. Beckmann et al. (1973) described the same phenomenon in Australian gilgai and referred to it as lattice gilgai (National Committee on Soil and Terrain 2009). On some washboard ridges, long, ridgelike microhighs extending from side slopes abruptly merge upslope on some summits with prominent, circular to ovoid gilgai microlows approximately 2 to 5 m in maximum diameter and intervening, somewhat reticulate microhighs. Although the terms *network gilgai* and *nuram* have been applied in the past (e.g., Beckmann et al. 1971; Paton 1974), this pattern of gilgai has been grouped in the category of *normal* gilgai in recent texts (e.g., National Committee on Soil and Terrain 2009). On the ascending ridge crests or on and around the summits of washboard ridges, areas of lattice and normal gilgai range in area from 0.025 to 2.6 ha, although most are of 1 ha or less in area. As few as a dozen, distinct gilgai microlows may exist in areas of normal gilgai on ascending ridge crests and summits. Two examples of the composite occurrence of gilgai formerly referred to as "depression gilgai" (e.g., Young 1976, 188) were identified in small ponds on nearly level summits in the study area. The floors of the ponds themselves, when desiccated, exhibit a faint geometric pattern that may be gilgai or desiccation cracks.

Compared to normal and lattice gilgai, far more land-surface area is covered with faint to very distinct, small-scale reticulate patterning (Fig. 6, top), which exists in areas as large as 15 ha, but normally over areas of less than 2.5 ha. Small-scale reticulate patterning exists on nearly level ground, chiefly around the margins of Wolf Butte in Dawes County and on the flattish summits of certain washboard ridges in north-central to northwestern Sioux County. It is a remarkably regular network of distinct to prominent linear elements that are 0.5 m or less in width, separating darker or lighter polygons approximately 1.5 to 3.0 m in diameter, making it of a distinctly smaller scale than the normal and lattice gilgai that is directly associated with linear gilgai elsewhere in the study area. It is also of a smaller scale than many examples of normal gilgai elsewhere (e.g., Khitrov 2016; Fig. 6, bottom). Whereas strata of the White River Group are mapped in the area of Wolf Butte, no such strata are currently mapped in the area of the reticulate-patterned summits in north-central to northwestern Sioux County, making it impossible, as yet, to propose a direct relationship between the patterning phenomenon and a single type of bedrock or soil parent material.

Soils

Soil series mapped in the study area are classified as Alfisols, Aridisols, Entisols, Inceptisols, Mollisols, and Vertisols (Natural Resources Conservation Service Soils n.d.; Soil Survey Staff n.d.). Gilgai, however, is clearly not restricted to soils that are officially mapped as Vertisols within the study area. We note that the original text explaining Soil Taxonomy (Soil Survey Staff 1975, 75) stated that Vertisols should exhibit "evidences [*sic*] of soil movement in the form of slickensides, gilgai microrelief, and wedge-shaped structural aggregates." We also note that subsequent editions of the keys to the same classification system do not include gilgai among the criteria distinguishing Vertisols, and the most recent version of the keys makes no mention at all of the phenomenon (Soil Survey Staff 2014). Approximately 95% of the linear gilgai that we mapped lies on areas mapped as Entisols of the Lohmiller, Orella, and Samsil series and Inceptisols of the Bufton and Pierre series (Table 1). In particular, most of the linear gilgai is on Aridic Ustorthents (Samsil), Vitrandic Haplustepts (Bufton), and Torertic Haplustepts (Pierre). Some 98% of the mapped normal and lattice gilgai lies on areas mapped as Entisols and Inceptisols (Bufton, Kyle, Pierre, and Samsil series), chiefly Aridic Ustorthents (Samsil) and

Torrertic Haplustepts (Pierre) (Table 1). The parent materials for soils on which we mapped linear, normal, and lattice gilgai are overwhelmingly residuum or transported alluvium ultimately derived from the weathering of shale (Natural Resources Conservation Service Soils n.d.), namely the Pierre Shale. Almost 80% of small-scale reticulate patterning that we describe lies on areas mapped as Entisols (Samsil) and Inceptisols (Bufton and Pierre) formed on the same kinds of parent materials (Table 1).

Discussion

The scale, geometry, and overall appearance of linear and lattice gilgai described in this article are entirely comparable with published accounts from elsewhere, and there are clear parallels for the development of gilgai on soils derived from the Pierre Shale (e.g., White and Bonestell 1960; Beckmann et al. 1971; Beckmann et al. 1973; Verster et al. 1973; Paton 1974; Khitrov 2016). Likewise, the intimate and systematic association of linear, normal, and lattice gilgai that we describe is effectively identical to far-flung locales (e.g., Beckmann et al. 1973; Verster et al. 1973). The much larger-scale, gilgai-hosting washboard terrain of this article is mostly the result of Late Pleistocene eolian erosion, which has been augmented by the erosive actions of mass wasting and running water. Other reports (Wayne and Guthrie 1993; Diffendal 1994; Joeckel et al. 2010) have drawn attention to a prominent, roughly northwest–southeast orientation of landforms in the northern to central Great Plains, including the present study area, and attributed it to erosion by strong prevailing winds during the Pleistocene and Holocene.

Although associated linear, lattice, and normal gilgai are readily identifiable in this study, the small-scale reticulate patterning (Fig. 6) visible on flattish surfaces in the study area is problematic. It is clearly a regular, or even systematic, pattern generally reminiscent of normal gilgai, but it is of a decidedly smaller scale than most examples thereof. Nevertheless, microrelief wavelengths as short as 1.8 to 2.0 m have been described from Vertisols (Khitrov 2016, table 2). Small-scale reticulate patterning may be (1) very small-scale gilgai microrelief; (2) the surface expression of large, deep soil desiccation cracks; or, quiet differently, (3) fractures produced by burial diagenetic processes that are utterly unrelated to soil shrink-swell, for which there is some precedent in the mudrocks of the White River Group (e.g., Maher and Shuster 2012).

Gilgai locations in the study area are, for the most part, clustered. This clustering may merely reflect the distribution of environmental conditions favoring the development of gilgai, although a perfunctory assessment of areal geography lends no supporting evidence to this hypothesis. The study area is small, so only microclimatic, rather than macroclimatic, factors should be at work in the differentiation of gilgai sites from non-gilgai sites. Gilgai definitely appears on both southwest-facing and northeast-facing sides lopes of washboard ridges and, therefore, microclimatic controls related to slope aspect are by no means absolute. The present distribution of gilgai in the study area may be less substantively related to the conditions of their *formation*, however, than to the means of their *destruction*. Linear gilgai identified herein ranges from pristine and very clearly defined to strongly eroded and less clearly defined. Grazing is the chief use of the local landscape, and cattle trails completely dissect the land surface in many places, most notably where numerous trails converge centripetally at a water tank. In such cases, nearby gilgai is patchy in its distribution and also in various stages of degradation. There are multiple places at which the side slopes of washboard ridges have been eroded by mass wasting, and apparently by large translational landslides in particular. There are other slopes on which gullies have developed parallel to the trend of linear gilgai and also severely eroded it. Slopes across the study area vary considerably in their degree and stage of erosion, whether by mass wasting or by running water, but it is clear that the entire landscape is a dynamic one affected by multiple processes, and not by gilgai formation alone. There are other parts of Nebraska in which soils developed on the Pierre Shale are widespread—particularly Boyd County, some 300 km to the east—and yet no gilgai has been found there. Landscapes, vegetation, parent material, relief, and even land use there are at least broadly similar to those of the study area, and even though rainfall is greater, gilgai is known to form elsewhere across a broad range of rainfall and temperature conditions.

Conclusions

There is no mistaking the existence of gilgai in the study area: it exists in numerous places on soils atop the Pierre Shale north of 42.5°N latitude in Dawes and

Table 1. Distribution of gilgai types by mapped soils in the study area.

Gilgai type	Soil series or mapping unit	Classification	Number of hectares
Linear	Arvada loam	Ustertic Natrargids	0.349
Linear	Bufton clay loam	Vitrandic Haplustepts	27.094
Linear	Kyle-Hisle complex	Torrertic Natrustalfs and Aridic Haplusterts	0.022
Linear	Kyle silty clay	Aridic Haplusterts	26.971
Linear	Lohmiller silty clay loam	Torrertic Haplustepts	0.683
Linear	Orella-badland complex	Aridic Ustorthents	0.634
Linear	Pierre clay	Torrertic Haplustepts	323.479
Linear	Pierre-Samsil silty clays	Torrertic Haplustepts and Aridic Ustorthents	79.065
Linear	Samsil silty clay	Aridic Ustorthents	76.794
Linear	Samsil-rock outcrop association	Aridic Ustorthents	6.477
Linear	Tassel-Ponderosa-rock outcrop complex	Ustic Torriorthents and Torriorthentic Haplustolls	0.186
Normal and lattice	Bufton clay loam	Vitrandic Haplustepts	0.764
Normal and lattice	Kyle silty clay	Aridic Haplusterts	0.336
Normal and lattice	Pierre clay	Torrertic Haplustepts	12.709
Normal and lattice	Pierre-Samsil silty clays	Torrertic Haplustepts and Aridic Ustorthents	0.202
Normal and lattice	Samsil silty clay	Aridic Ustorthents	4.674
Normal and lattice	Samsil-rock outcrop complex	Aridic Ustorthents	0.050
Small-scale reticulate	Bufton clay loam	Vitrandic Haplustepts	8.533
Small-scale reticulate	Norrest silty clay loam	Aridic Haplustalfs	6.804
Small-scale reticulate	Pierre clay	Torrertic Haplustepts	54.408
Small-scale reticulate	Pierre-Samsil silty clays	Aridic Ustorthents	9.593
Small-scale reticulate	Samsil silty clay	Aridic Ustorthents	0.218
Small-scale reticulate	Tassel-Ponderosa-rock outcrop association	Ustic Torriorthents and Torriorthentic Haplustolls	12.378

Sioux Counties. In retrospect, this discovery might be expected relative to a small body of research conducted in South Dakota more than four and a half decades ago (e.g., White and Bonestell 1960; White and Agnew 1968; White 1970), but there has been exceedingly little research on gilgai in the Great Plains since then and, prior to this article, it seems, none at all in Nebraska. Gilgai in far northwestern Nebraska appears to be severely degraded in many places by the movements of cattle. Local gullying and landsliding may also have removed gilgai from slopes. Some of this gilgai degradation and erosion is attributable to human land use. A cursory comparison of the present study area with another Pierre Shale landscape lacking gilgai, far to the east in Nebraska, hints that some soil-forming factor other than climate, parent material, organisms, and relief—perhaps landscape age—has been of prime importance in determining whether or not gilgai ever formed on suitable soil parent materials in the region. There are substantial opportunities for future pedological, geological, and ecological research on gilgai in Nebraska and the Great Plains, and also on the past and present evolution of unique Pierre Shale landscapes. Finer-scale soil mapping and investigation and more detailed geologic mapping will be needed in order to articulate the phenomenon of gilgai development within a comprehensive framework of landscape development on Pierre Shale terrain. Such fieldwork should include onsite measurements of gilgai, soil pit studies across microhighs and microlows, and assessments of any physical contrasts between slopes with and without gilgai within the present study area.

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References

Beckmann, G. G., G. D. Hubble, and C. H. Thompson. 1971. "Gilgai Forms, Distribution, and Soil Relationships in North-Eastern Australia." In *Proceedings of the Symposium on Soils and Earth Structures in Arid Climates*, 118–21. Adelaide: Australian Geomechanics Society.

Beckmann G. G., C. H. Thompson, and G. D. Hubble. 1973. "Australian Landform Example No. 22: Linear Gilgai." *Australian Geographer* 12 (4): 363–66.

Blackburn, G. 1974. "Distribution of Linear Gilgai: A Comment." *Australian Geographer* 12 (6): 564.

Blokhuis, W. A., M. J. Kooistra, and L. P. Wilding. 1990. "Micromorphology of Cracking Clayey Soils (Vertisols)." In *Soil Micromorphology: A Basic and Applied Science*, ed. L. A. Douglas, 123–40. Developments in Soil Science 19. Amsterdam: Elsevier.

Brierly, J. A., H. B. Stonehouse, and A. R. Mermut. 2011. "Vertisolic Soils of Canada: Genesis, Distribution, and Classification." *Canadian Journal of Soil Science* 91:903–16.

Crook, K. A. W. 1958. "'Finger-Print' Pattern on Certain Calcareous Soils—A Suggestion." *American Association of Petroleum Geologists Bulletin* 42 (12): 3001.

Diaz, N., F. Dietrich, G. Cailleau, D. Sebag, B. Ngounou Ngatcha, and E. Verrecchia. 2016. "Can Mima-Like Mounds be Vertisol Relics (Far North Region of Cameroon, Chad Basin)?" *Geomorphology* 261:41–56.

Diffendal, R. F. Jr. 1994. "Geomorphic and Structural Features of the Alliance 1° X 2° Quadrangle, Western Nebraska, Discernible from Synthetic-Aperture Radar Imagery and Digital Shaded-Relief Maps." *Contributions to Geology, University of Wyoming* 30 (2): 137–47.

Duffield, L. F. 1970. "Vertisols and Their Implications for Archaeological Research." *American Anthropologist*, n.s., 72 (5): 1055–62.

Gabet, E. J., J. T. Perron, and D. L. Johnson. 2014. "Biotic Origin for Mima Mounds Supported by Numerical Modeling" *Geomorphology* 206:58–66.

Goudie, A. S., M. J. S. Sands, and I. Livingstone, 1992. "Aligned Linear Gilgai in the West Kimberley District, Western Australia." *Journal of Arid Environment*s 23:157–67.

Gustavson, T. C. 1975. "Microrelief (Gilgai) Structures on Expansive Clays of the Texas Coastal Plain—Their Recognition and Significance in Engineering Construction." Geological Circular 75–7. Austin: Bureau of Economic Geology, University of Texas at Austin.

Hallsworth, E. G., and G. G. Beckman. 1969. "Gilgai in the Quaternary." *Soil Science* 107 (6): 409–20.

Hallsworth, E. G., G. K. Robertson, and F. R. Gibbons. 1955. "Studies in Pedogenesis in New South Wales, VII: The Gilgai Soils." *Journal of Soil Science* 6:1–31.

Hartley, P. E., D. R. Presley, M. D. Ransom, G. M. Hettiarachchi, and L. T. West. 2014. "Vertisols and Vertic Properties of Soils of the Cherokee Prairies of Kansas." *Soil Science Society of America Journal* 78 (2): 556–66.

Jensen, H. I. 1911. "The Nature and Origin of Gilgai Country." *Proceedings of the Royal Society of New South Wales* 45:337–58.

Joeckel, R. M., J. S. Dillon, P. R. Hanson, L. M. Howard, and M. S. Kuzila. 2010. "The Ridges of Boyd County: Oriented Landforms and Late Quaternary Eolian Processes in North-Central Nebraska, USA." *Geological Society of America Abstracts with Programs* 42 (5): 417.

Kabala, C., T. Plonka, and A. Przekora. 2015. "Vertic Properties and Gilgai-Related Subsurface Features in Soils of South-Western Poland." *Catena* 128:95–107.

Khitrov, B. 2016. "Vertisols with Gilgai Microtopography: Classification and Parameters of Microtopography and Morphological Types of Soils (a Review)." *Eurasian Soil Science* 49 (2): 143–63.

Kovda, I. V., A. M. Ermolaev, A. A. Gol'eva, and E. G. Morgun. 1999. "Reconstruction of Gilgai Landscape Elements According to Botanical and Biomorph Analysis." *Biology Bulletin* 26:297–306.

Maher, H., and Shuster, R. 2012. "Chalcedony Vein Horizons and Clastic Dikes in the White River Group as Products of Diagenetically Driven Deformation." *Lithosphere* 4 (3): 167–86.

Mathewson, C. C., J. P. Castleberry II, and R. L. Lytton. 1975. "Analysis and Modeling of the Performance of Home Foundations on Expansive Soils in Central Texas." *Bulletin of the Association of Engineering Geologists* 12 (4): 275–302.

McKenzie, N., D. Jacquier, R. Isbell, and K. Brown. 2004. *Australian Soils and Landscapes: An Illustrated Compendium.* Clayton, Victoria: CSIRO Publishing.

Mermut, A. R., G. S. Dasog, and G. N. Dowuona. 1996. "Soil Morphology." In *Vertisols and Technologies for Their Management*, ed. N. Ahmad and A. Mermut, 89–114. Developments in Soil Science 24. Amsterdam: Elsevier.

Mermut, A. R., D. D. Patterson, and P. A. McDaniel. 1996. "Cold Vertisols and Their Management." In *Vertisols and Technologies for their Management. Developments in Soil Science 24*, ed. N. Ahmad and A. Mermut, 475–98. Amsterdam: Elsevier.

Milne, A. E., R. Webster, and R. M. Lark. 2010. "Spectral and Wavelength of Gilgai Patterns from Air Photography." *Australian Journal of Soil Research* 48 (4): 309–25.

National Committee on Soil and Terrain. 2009. *Australian Soil and Land Survey Field Handbook*. 3rd ed. Collingwood, Victoria, Australia: CSIRO Publishing.

Natural Resources Conservation Service Soils. n.d. "Official Soil Series Descriptions (OSDs)." https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/home/?cid=nrcs142p2_053587.

Paton, T. R. 1974. "Origin and Terminology for Gilgai in Australia." *Geoderma* 11:221–42.

Prescott, J. A. 1931. "The Soils of Australia in Relation to Vegetation and Climate." Commonwealth of Australia Council for Scientific and Industrial Research Bulletin 52.

Ruppert, D. E. 2017. "Southwest Plateaus and Plains Range and Cotton Region and Southwestern Prairies Cotton and Forage Regions: LRRs I and J." In *The Soils of the USA*, ed. L.T. West, M.J. Singer, and A.E. Hartemink, 165–90. Cham, Switzerland: Springer.

Russell, J. S., A. W. Moore, and J. E. Coaldrake. 1967. "Relationships between Subtropical Semiarid Forest of *Acacia harpophylla* (Brigalow), Microrelief, and Chemical Properties of Associated Gilgai Soils." *Australian Journal of Botany* 15 (3): 481–98.

Soil Science Society of America. n.d. "Glossary of Soil Science Terms." https://www.soils.org/publications/soils-glossary#.

Soil Survey Staff. n.d. "Soil Survey Geographic (SSURGO) Database." https://sdmdataaccess.sc.egov.usda.gov.

Soil Survey Staff. 1975. *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*. Agriculture Handbook 436. Washington, DC: USDA Soil Conservation Service.

Soil Survey Staff. 2014. *Keys to Soil Taxonomy*, 12th ed. Washington, DC: USDA Natural Resources Conservation Service.

Tanner, W. F. 1958. "'Finger-Print' Pattern on Certain Calcareous Soils." *American Association of Petroleum Geologists Bulletin* 42 (2): 438–40.

Thompson, C. H., and G. G. Beckmann. 1982. "Gilgai in Australian Black Earths and Some of Its Effects on Plants." *Tropical Agriculture* 59:149–56.

Verger, F. 1964. "Mottureaux et Gilgais." *Annale de Géographie* 73 (398): 413–30.

Verster, E., J. M. de Villers, and J. C. Scheepers. 1973. "Gilgai in the Rustenburg Area." *Agrochemophysica* 4:57–62.

Warren Wilson, J., and J. H. Leigh. 1964. "Vegetation Patterns on an Unusual Gilgai Soil in New South Wales." *Journal of Ecology* 52 (2): 379–89.

Wayne, W. J., and R. S. Guthrie. 1993. "Permafrost and Periglacial Winds around the Wisconsinan Ice Margin in the Northern Plains of the USA." In *Proceedings, Permafrost, Sixth International Conference*, 694–99. Wuschan: South China University of Technology Press.

Weitkamp, W. A., R. C. Graham, M. A. Anderson, and C. Arnheim. 1996. "Pedogenesis of a Vernal-Pool Entisol-Alfisol-Vertisol Catena in Southern California." *Soil Science Society of America Journal* 60 (1): 316–23.

White, E. M. 1970. "Soil Cycling and Texture Differentiation in Wavy Gilgai." *Proceedings of the South Dakota Academy of Sciences* 49:90–97.

White, E. M. and A. F. Agnew. 1968. "Contemporary Formation of Patterned Ground by Soils in South Dakota." *Geological Society of America Bulletin* 79 [7]: 941–44.

White, E. M., and R. G. Bonestell. 1960. "Some Gilgaied Soils in South Dakota." *Soil Science Society of America Proceedings* 24:305–9.

Wilding, L. P., I. V. Kovda, E. G. Morgun, and D. Williams. 2002. "Reappraisal of the Pedon Concept for Vertisols: Consociations or Complexes?" *Transactions of the 17th World Congress of Soil Science*. Paper No. 872.

Wilding, L. P., and D. Tessier. 1988. "Genesis of Vertisols: Shrink-Swell Phenomena." In *Vertisols: Their Distribution, Properties, Classification and Management*, ed. L. P. Wilding and P. Puentes, 55–81. US Department of Agriculture Soil Management Support Services, Technical Monograph 18. College Station: Texas A&M University Printing Center.

Wilding, L. P., D. Williams, D., W. L. Miller, T. Cook, T., and H. Eswaran. 1990. "Close Interval Spatial Variability of Vertisols: A Case Study in Texas." In *Proceedings 6th International Soil Correlation Meeting (VI ISCOM): Characterization, Classification and Utilization of Cold Aridisols and Vertisols*, ed. J. M. Kimble, 232–47. Lincoln, NE: US Department of Agriculture, Soil Conservation Service, National Soil Survey Center.

Williams, D., T. Cook, W. Lynn, W., and H. Eswaran. 1996. "Evaluating the Field Morphology of Vertisols." *Soil Survey Horizons* 37:123–31.

Williams, O. B. 1955. "Studies in the Ecology of the Riverine Plain, I: The Gilgai Microrelief and Associated Flora." *Australian Journal of Botany* 3:99–112.

Wondzell, S. M., J. M. Cornelius, and G. L. Cunningham. 1990. "Vegetation Patterns, Microtopography, and Soils on a Chihuahuan Desert Playa." *Journal of Vegetation Science* 1:403–10.

Young, A. 1976. *Tropical Soils and Soil Survey*. Cambridge: Cambridge University Press.

Zangerlé , A., D. Renard, J. Iriarte L. E. Suarez Jimenez, K. L. Adame Montoya, J. Juilleret, and D. McKey. 2016. "The *Surales*: Self-Organized Earth-Mound Landscapes Made by Earthworms in a Seasonal Tropical Wetland." *PLoS ONE* 11 (5): e0154269. doi:10.1371/journal.pone.0154269.