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Agrarian legacy in soil nutrient pools of urbanizing arid lands

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Abstract

Today's worldwide expansion of dry land cities consumes cultivated and native ecosystems, providing laboratories for investigating imprints of former land use in places where people now live. Around Phoenix, USA, we compared soil nutrient pools in residential yards converted from farms with nutrient pools in yards developed on native desert. Organic matter, carbon (C), nitrogen (N), and soluble ions were $>$2-fold greater in yards that were previously agrarian than in yards that were not. These pools remain elevated 40 years after land conversion to residential use. Present N accumulation ($1.5\,g\,m^{-2}\,yr^{-1}$) is not affected by prior land use, suggesting that rates of residential fertilizer application and retention are not affected by antecedent soil fertility. Bioavailable, inorganic phosphorus (P_{av}) is elevated in soil with a recent agrarian past, but this signal disappears after 10–30 years of residential use owing to an accumulation of P_{av} in never-farmed yards. Our results indicate a 'direct agrarian legacy,' wherein agrarian amendment of nutrient pools endures urbanization, more so than an 'indirect legacy,' wherein present land management is molded by former land use. Agriculture in dry lands thus sequesters material in soils, and—as we also found higher material contents in residential soils than in contemporary agrarian soils—residential land use simply adds to the agrarian legacy these soils already bear. Intense human use of arid lands may cause increases in material pools in soils, a condition with potential global consequence.

Key words: agriculture, Arizona, carbon, climate change, conductivity, land use change, legacy, nitrogen, nutrient, phosphorus, residential, soil, urban ecosystem

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Introduction

Humans have transformed Earth's surface in pursuit of water, food, fiber, and fuel (Reid *et al*., 2005). The expansion of urban centers and their supporting lands figures prominently in these changes (Cronan, 1991; Luck *et al*., 2001). Although cities are home to most of humanity (United Nations, 2004), we cannot predict the conditions to which these billions of people will be daily exposed. Why? Too little research has investigated whether, and for how long, ecosystems bear the influence of what they used to be (Foster *et al*., 2003).

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Here, we investigate land-use legacies around Phoenix to determine whether the identity of the prior land-use types influences soil biogeochemical pools in a contemporarily urban ecosystem. Earth's dry lands and their $10^7\,km^2$ of cultivation are being urbanized at unprecedented rates (Ayyad, 2003; Pickett *et al*., 2004). Urbanization of dryland farms may have biogeochemical consequences that differ from those accompanying farmland transformations in other biomes (Burke *et al*., 1995). In temperate regions, soil organic matter (SOM) pools often decline during cultivation (Murty *et al*., 2002) and accrue during the regrowth of forests and grasslands (Houghton *et al*., 1999; Kaye *et al*., 2000). In dry regions, however, farms replace native ecosystems with inherently small soil nutrient pools (Jobbágy & Jackson, 2000). Soils with initially low pools and those in dry lands may gain rather than lose C and SOM upon land transition out of natural cover (Mann, 1980; Jackson *et al*., 2002; Zhu *et al*. in Press). Additionally, socioeconomic pressures may dictate that farms are not given over to forest and grassland recovery, but rather to urban uses (particularly in dry lands, Cooke *et al*., 1982) with their own biogeochemical dynamics (Grimm *et al*., 2004).

We compared soil nutrient and C pools between residential land with and without agrarian history. Where differences were evident, we investigated three alternative hypotheses (Table 1) for when, in the historical sequence of land-use transitions, those differences emerged.

Methods

Around metropolitan Phoenix, we compared soils on residential parcels that were either converted from agrarian use or converted from unmanaged desert. In this arid–hyperarid region, mean annual rainfall is 19.4 cm, mean January minimum temperature is 5.3 °C, and mean June–September maximum monthly temperatures are >35 °C (Fossum *et al*., 2001). The urban population has doubled 5.8 times since 1940 (US Census Bureau). The urbanized area has increased from 306 km^2 in 1955 to 2058 km^2 in 1995. Of the new urban area, 725 km^2 were previously agrarian and the rest previously desert. Over a similar time frame (1952–1997), irrigated agrarian lands in central Arizona have declined from 2300 to 1200 km^2 (Maricopa County agricultural data). Soils are typic aridisols.

Data collection and analysis

To identify sample sites we obtained a spatially random array of 204 coordinates (Hope *et al*., 2003), dispersed over 6400 km^2. Land cover at each point was classified for nine time points between 1912 and 2000 (Central Arizona-Phoenix Long-Term Ecology Research project, http://seinet.asu.edu/). This array yielded 16 residential parcels converted from >20 years of agrarian use (where agrarian use commenced before 1912) and 23 parcels converted from desert cover. For each parcel, we obtained the year of transition to residential use (YoT) from the Maricopa County Tax Assessor. In each parcel, a composite soil sample was obtained by combining four, 10 cm deep soil cores taken from the corners of a 200 m^2 square. Sieved (<2 mm), dried (60 °C) soils were analyzed for total C and total N using combustion; for bioavailable, inorganic phosphorus (P_{av}) using colorimetric analysis of sodium bicarbonate ($NaHCO_3$) extract; for SOM using loss on ignition at 550 °C for 2 h; and for conductivity in a 1 : 1 soil : water slurry. The density of rock-free, dry, soil (estimated by volumetric soil coring) converted C, N, P_{av}, and SOM concentrations to mass $X\,m^{-2}$ ground surface area, integrated through 10 cm depth. Soil density did not differ between yards with and without an agrarian past (ANOVA, $P = 0.96$).

Soil constituents (log-10 transformed) were analyzed with general linear models as functions of transition type (agrarian to residential vs. desert to residential), YoT, and the interaction between transition type and YoT. We considered the 'indirect agrarian legacy' hypothesis (see Table 1) to be supported when we observed a significant interaction term, which indicates that soil differences between once-farmed and never-farmed lands change after transition to residential occupancy.

For the 'preagrarian legacy' hypothesis, we investigated whether patterns observed from residential lands might have arisen from natural landscape variability that existed before modern agriculture or urbanization. We used data from 48 desert sites, randomly arrayed throughout the same 6400 km^2 study region, and obtained with analytical methods identical to those described above. Two types of analyses were conducted. (1) As younger floodplain terraces at low elevations tend to be cultivated first owing to the ease of transporting water to them, we sought evidence of elevation gradients in the nutrient pools of desert soils. The desert soils for this analysis ranged from mountain slopes to older floodplains (Holocene and Pleistocene) to younger floodplains (Holocene). Younger floodplain soils were similar in landform and landscape position to most of the agricultural soils in the region, but were never cultivated owing to socioeconomics or canal engineering. (2) We investigated whether the range and variance in residential soil data were matched by desert–land soil data. Such a match raises the possibility that a difference between once-farmed and never-farmed yards is an artifact of natural, background variability. For this analysis, we conducted two-sample Kolmogorov–Smirnov (K–S) tests comparing distribution functions of soil nutrients between desert and residential soils.

Results

Soil conductivity, SOM, and C were greater in residential yards converted from agrarian land than in yards converted from desert (Fig. 1). Conductivity was 2.2-fold greater ($P = 0.007$, $R^2 = 0.18$), SOM was 2.2-fold greater ($P < 0.001$, $R^2 = 0.47$), and C was 2.3-fold greater ($P < 0.001$, $R^2 = 0.36$) in yards on previously farmed land. These soil properties were not correlated with yard age in either once-farmed or never-farmed yards (YoT and YoT × transition type, $P > 0.12$).

Table 1 Legacy hypotheses for the observation that there are ecological differences between lands of different historical but similar contemporary uses

Hypothesis	Description	Stated generally
(1) Preagrarian legacy	Prior to farming activity, soil nutrient and C pools differed between lands that were, and were not eventually farmed	Ecological differences result from naturally occurring phenomena that predate the time period in which land use differed
(2) Direct agrarian legacy	Differences in soil nutrient and C pools between once-farmed and never-farmed land derive directly from agrarian practices and persist despite subsequent urbanization	Ecological differences result directly from differences in historical land use
(3) Indirect agrarian legacy	Differences in soil nutrient and C pools between once-farmed and never-farmed yards emerged after urbanization because yard management/maintenance is shaped by historic land use	Ecological differences develop during the contemporary period of similar land use because land management is molded by historical land use

These hypotheses are not mutually exclusive.

Soil N was greater in residential yards converted from agrarian land than in yards converted from desert (transition type, $P<0.001$). Additionally, N was greater in older yards (Fig. 2a; YoT $P=0.004$). The YoT $\times$ transition type interaction term had $P=0.073$. The rate of increase in N content with yard age is 1.2–1.9 $\mathrm{g\,N\,m^{-2}\,yr^{-1}}$, with the lower estimate from a bias-corrected back-transformation of the slope and the higher estimate from the slope of a similar figure using untransformed data. Excluding the interaction term, $R^2=0.50$. Comparing least-squares means (adjusted for the covariate, YoT), N was 2.1-fold greater in yards on previously farmed land.

Soil P_{av} also exhibited a correlation with YoT, but the relation with YoT was affected by yard history (Fig. 2b, YoT $\times$ transition type, $P=0.023$). Owing to the significant interaction term, we separately evaluated the two historical categories of yard for the correlation between YoT and soil P_{av}. The correlation was not significant for yards with an agrarian history ($P=0.560$, $R^2=0.03$), and was significant for yards without an agrarian history ($P=0.006$, $R^2=0.32$), wherein soil P_{av} content increased 0.03–0.04 $\mathrm{g\,P\,m^{-2}\,yr^{-1}}$. In all analyses, the significance of P values and the direction of effects are similar without the three pre-1950 points seen in Fig. 2.

Our other suite of analyses was of desert soils. First, we investigated possible elevation gradients in soil nutrient pools. The correlation between elevation and soil nutrient pool was not statistically significant for any of the five soil properties we examined ($P>0.10$). Second, we compared distribution functions in nutrient pools between desert and residential soils. K–S tests were significant for conductivity, SOM, and C (all $P<0.001$) and for N ($P=0.024$), indicating that frequency distributions were broader and skewed to larger values for data from residential soils than for data from desert soils. The K–S test was not significant ($P=0.115$) for P_{av}.

Discussion

Webster's Dictionary defines a legacy as 'something resulting from and left behind by an action, event, or person.' Our data suggest that nutrient pools in dryland residential soils are a mix of direct and indirect legacies of prior land use. They also demonstrate how contemporary residential activities may be changing pools, and have implications for global change.

Agrarian legacies in soil chemistry

Data for soil conductivity and SOM, C, and N contents do not support the 'preagrarian legacy' or 'indirect agrarian legacy' hypotheses. Two sources of information overturn the 'preagrarian legacy' hypothesis. First, the targets for aridland cultivation are not inherently more fertile, as we observed no systematic changes in the nutrient pools of desert soils across an elevation gradient from slopes to floodplains. Second, the range and variability of nutrient pools that occur in desert

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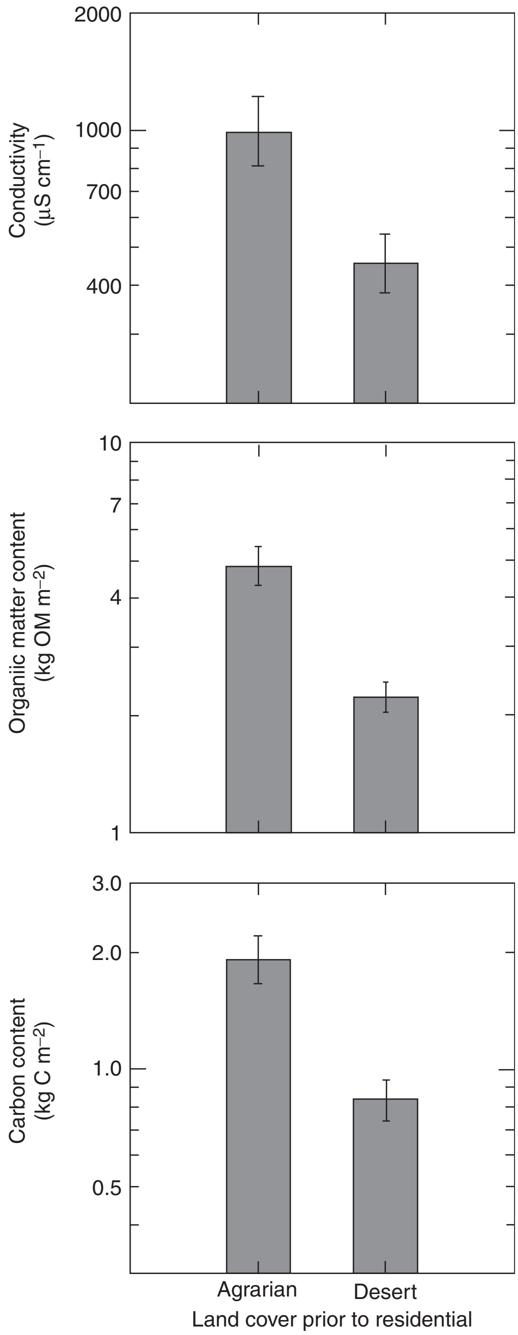

Fig. 1 Responses of soil constituents to land use history. Year of transition (YoT) and the YoT × transition type interaction term were not significant, so we display the highly significant influence of transition type. Bars show means and error bars show one standard error of the mean. Organic matter and C contents are of the top 10 cm of soil.

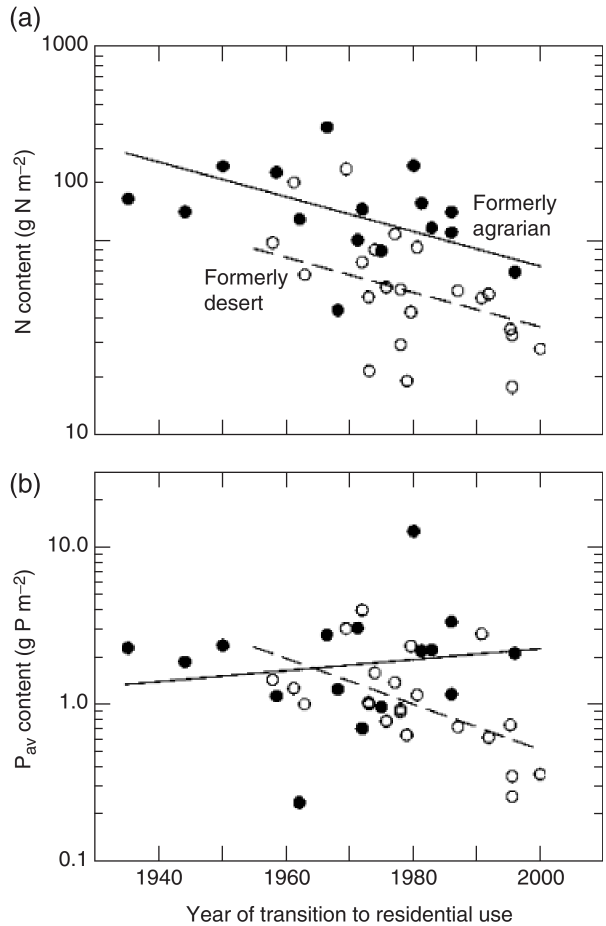

Fig. 2 Responses of (A) soil N and (B) P_{av} to land use history and Year of transition (YoT). Residential yards on lands previously agrarian are depicted with •, and yards on lands previously desert are depicted with ○. Nutrient contents are of the top 10 cm of soil.

soils are unlikely to produce the patterns we observed in residential soils (shown with the K–S test). Thus, differences in soil properties that we observed between residential parcels of former agrarian use and parcels of former desert cover probably did not exist before agriculture commenced.

Information on house age casts doubt on the 'indirect agrarian legacy' hypothesis. The YoT × transition type interaction term was not significant for SOM, C, N, and conductivity. Thus, between residential parcels of prior agrarian use and parcels of prior desert cover, differences existed before the land became residential.

Data for soil conductivity and SOM, C, and N content support the direct agrarian legacy hypothesis. These soil constituents are enhanced on formerly farmed land 40 years after that land had been converted to residential use, and the other two hypotheses do not explain this enhancement. Greater pool sizes probably result from additions of material, not from soil compaction caused by farming activities, as soil density was statistically similar between yards of former agrarian and of former desert cover. Agriculture may increase conductivity by introducing ions to the soil surface in irrigation water, from deeper soil via irrigation-induced capillary rise and vaporization of phreatic water (Mohamed *et al*., 2000), and from deeper soil via crop roots (Jobbágy & Jackson, 2001). Agriculture may amend C by elevating inputs of crop residue and root-derived C inputs more than it stimulates microbial respiration and erosion rates. Arid-land agriculture may also amend C by enhancing calcite ($CaCO_3$) deposition (Schlesinger, 1985). Because the increase in agricultural soils (relative to desert soils) of total soil C is less than half the increase of SOM (Fig. 1), and because $CaCO_3$ typically accumulates at depths beneath our samples (Schlesinger, 1985), the agrarian amendment of C probably derives from organic C accumulation. Cultivation may amend N by enhancing rates of atmospheric N_2 fixation by microbial symbionts of alfalfa (*Medicago sativa*), by fertilizer N applications and subsequent assimilation into stable SOM pools (Kaye *et al*., 2002), and by N translocation from deeper soil layers by crop roots (Jobbágy & Jackson, 2001).

N accumulation in residential soils

Nitrogen aggrades in this urban ecosystem. This conclusion is supported by two independent sources of information. We estimate that the N pool in the top 10 cm of residential soil grows 1.2–1.9 $g\,N\,m^{-2}\,yr^{-1}$. Using mass balance, Baker *et al*. (2001) calculate an N budget of the watershed ecosystem that contains the Phoenix metropolis and its fringing agricultural and desert lands. They estimate an N accumulation rate of 1.4–1.7 $g\,N\,m^{-2}\,yr^{-1}$. Given that the desert portion of Baker *et al*.,'s study area probably accumulates 0.06 $g\,N\,m^{-2}\,yr^{-1}$ (Peterjohn & Schlesinger, 1990), and the impervious urban portion probably accumulates no N on annual time scales, accumulation in nondesert soils would need to be higher than 1.4–1.7 $g\,N\,m^{-2}\,yr^{-1}$ for Baker *et al*.'s entire study area to accumulate N at this rate. Thus, accumulation in yards is probably at the higher end of our estimated range.

Nitrogen accumulation in yards might be explained by many competing hypotheses. One hypothesis is that residential occupants manage yards in a manner that decreases rates of loss. This hypothesis is unlikely, as both N loss and N loading rates increase in human-dominated ecosystems (Vitousek *et al*., 1997). Residential activities such as flood irrigation, cultivation of woody vegetation, and disposal of lawn clippings probably hasten N loss through leaching, aboveground plant uptake, and litter export (Kaye *et al*., 2005).

Another hypothesis for ongoing N accumulation in yards is that residential occupants elevate both N loss and N loading rates, but elevate loading rates to a greater degree. Forms of loading that might explain N accumulation through time in residential soils include NO_x deposition and soil fertilization. NO_x deposition largely derives from the fixation of atmospheric N_2 by combustion processes in automobiles. If combustion-derived NO_x emissions in our study region are 2.7 $g\,NO_x\text{-}N\,m^{-2}\,yr^{-1}$ (Heisler *et al*., 1997; Baker *et al*., 2001), and 52% of emitted NO_x is deposited in its modeled air shed (Russell *et al*., 1993), then NO_x deposition to yards could be 1.4 $g\,N\,m^{-2}\,yr^{-1}$. Even if 100% of deposited NO_x-N were retained, this value is near the lower, and less likely, end of our estimated range. A second explanation for N accumulation in yards is fertilizer application. We estimate fertilizer application to yards at 11.2 $g\,N\,m^{-2}\,yr^{-1}$, based on the recommended rates (22.3 $g\,N\,m^{-2}\,yr^{-1}$) of fertilizer application (Doerge *et al*., 1991) and the estimate that half of Phoenix-area yards are fertilized (Baker *et al*., 2001). Thus, 11–17% of applied fertilizer N need be retained to achieve an increase of 1.2–1.9 $g\,N\,m^{-2}\,yr^{-1}$. We deem fertilizer application and partial retention a highly likely explanation for N accumulation in residential soils.

If fertilizer application underlies the accumulation of N in residential soils, the definition of 'legacy' may need refinement for ecological contexts. An agricultural effect on soil N, persisting after agrarian practices cease, is an empirical reality. Yet, the consequences of this reality on the subsequent socio-ecological system are unclear. Enduring amendments of agrarian-derived N will probably affect N cycling. Decisions about yard fertilization, however, appear unaffected by antecedent soil conditions. These observations raise the question, is a legacy merely 'something. . .left behind,' something with consequences for other ecological processes, or something with notable impacts on human behaviors?

P accumulation in residential soils

P_{av} content only increases with yard age in soils with no agrarian history. Consequently, the disparity in P_{av} between yards of prior agrarian use and yards of prior desert cover disappears after 10–30 years. Enhancement of P by agrarian activity does persist, as P_{av} does not decline with time since agrarian cessation; but, the agrarian signal disappears because residential activities accumulate P_{av} in the 'reference' yards (i.e. those never cultivated). One view, therefore, is that owing to the nature of the subsequent land use (i.e. residential), there is no agrarian legacy (or only a brief one) on the P_{av} content of soil. Why do residential activities cause P_{av} to increase in prior desert but not prior agrarian soils? One hypothesis is that $NaHCO_3$-extractable P is so mobile that P_{av} pools have a constrained scope for growth, as new, elevated inputs of phosphate (PO_4^{3-}) rapidly enter biomass and sorbed mineral pools.

Urban development of agrarian land

As our results pertain to material accounting on lands in transition, we provide an additional, brief analysis of urbanization of agrarian land. Our residential sites of agrarian history, compared with eight central Arizona sites (from the same soils dataset) of contemporary agrarian use (agrarian since pre-1912), have soils enriched in OM (5.2 vs. $3.3\,kg\,m^{-2}$ in the top 10 cm; $P = 0.015$), C (2.1 vs. $1.0\,kg\,m^{-2}$; $P < 0.001$), and N (154 vs. $93\,g\,m^{-2}$; $P = 0.051$). Thus, an urban effect is building atop the agrarian legacy these soils already bear, with potentially global consequences for material sequestration in soils of the human-dominated portion of the arid world.

Legacies and global change

The contemporary state of an ecological system is contingent on prior states (Connell, 1980; Facelli & Pickett, 1990), including land use. Prior land uses can influence ecological systems after they cease to operate and after the signal of more recent disturbances are layered over them (Zimmerman *et al*., 1995; Motzkin *et al*., 1996; Willig *et al*., 1996; Harding *et al*., 1998; Foster *et al*., 2003). Understanding the causes and durations of legacies may improve management of ecological systems, particularly ones exhibiting slowly changing variables and hysteresis (Clark *et al*., 2001).

Our analysis shows that despite myriad human perturbations to urban soils, a widespread, general, and lasting legacy of agriculture is detectable across the highly variable soils of Phoenix. The impact of this legacy is not subtle—it results in a two-fold increase in some soil nutrient and carbon pools. This agrarian legacy not only defines the environment of the city, but also is related to the important ecosystem services of soil C and N sequestration.

Legacies should perhaps be considered when developing strategies to mitigate greenhouse gas emissions and eutrophication. One present strategy is to sequester C and N in soil by ceasing agrarian practices. In humid regions, agrarian practices typically deplete SOM pools (Burke *et al*., 1995; Compton *et al*., 1998; Knops & Tilman, 2000; Murty *et al*., 2002) by stimulating decomposition and mineralization, hastening erosion, and exporting crops and litter (Richter *et al*., 2000; Grünzweig *et al*., 2003). In arid lands, agricultural practices may amend soils with SOM, C, and N, which remain in soil through decades of subsequent residential occupation. Potentially offsetting the soil storage of materials that we observed, are the C and N releases that occur in any modern farming system (Schlesinger, 1999). Nevertheless, land use and demographic change in arid and semi-arid biomes will be globally pervasive and will outpace changes in humid biomes (Middleton & Thomas, 1997; United Nations, 2004). The possible net storage in dry lands of soil constituents—caused by conventional agriculture and sustained despite urbanization—should, thus, be considered in global evaluations of land use change.

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