

Livestock and meat consumption reductions may yield limited improvements in groundwater quality

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Abstract

Reducing meat consumption is increasingly proposed as a strategy for lowering agricultural nitrogen pollution. Yet groundwater does not respond directly or immediately to changes in livestock production: nitrogen moves through interconnected crop–livestock systems and is subsequently filtered by soils, aquifers and decades of legacy contamination. Whether livestock reduction alone can therefore deliver the anticipated groundwater benefits remains unresolved. Here we connect 30,340 groundwater observations from 14,995 wells across the conterminous United States with agricultural production, hydrogeology, climate and the geography of meat-sector facilities. Across complementary statistical, predictive and scenario analyses, groundwater nitrate was more consistently organized by crop-production pressures and aquifer susceptibility than by livestock or current meat-processing geography alone. This distinction materially altered the benefits attributed to food-system change. Halving livestock and manure pressure reduced predicted national nitrate-exceedance risk by 3.7%, whereas a coordinated transition that also reduced feed-crop area, cropland and fertilizer demand produced a 9.2% reduction. These modeled contrasts are not causal forecasts of dietary change, but they expose a critical systems constraint: removing animals without reorganizing the nitrogen demands that surround them yields limited groundwater improvement. Effective food-system transitions must therefore couple changes in livestock production with crop and fertilizer management while accounting for the long and spatially uneven memory of groundwater.

1. Introduction

Global livestock supply chains release approximately 65 Tg of reactive nitrogen each year—about one-third of anthropogenic nitrogen emissions—and nearly 70% of this burden arises from producing animal feed rather than from animals alone (Uwizeye et al., 2020). Reducing meat consumption has therefore emerged as a prominent strategy for lowering agricultural nitrogen losses alongside greenhouse-gas emissions, land demand and other environmental pressures (Poore & Nemecek, 2018; Springmann et al., 2018). Yet the water-quality consequences of such a transition are not determined simply by the number of animals removed. Livestock production connects feed crops, synthetic fertilizer, manure recycling and food-processing activities within a shared nitrogen system. Reducing animal numbers may lower manure generation and feed demand, but the resulting benefit depends on which crops or foods replace animal products, whether displaced manure is replaced by synthetic fertilizer, and where the reorganized production occurs (van Zanten et al., 2023; White & Hall, 2017). The relevant question is therefore not whether livestock contributes to nitrogen pollution—it clearly does—but whether reducing livestock pressure alone produces a distinct and measurable improvement in groundwater quality once the surrounding crop-production system is considered.

Groundwater makes this question especially consequential—and unusually difficult to answer. By 2020, the global vadose zone was estimated to contain $4,037 \pm 214$ Tg N as nitrate, more than 25 times the 162 ± 6 Tg N accumulated in shallow groundwater; modeled concentrations exceeded the WHO drinking-water guideline across approximately 10% of global land area (Zhao et al., 2026). This subsurface reservoir means that nitrate observed today is not a contemporaneous record of agricultural activity but the accumulated outcome of historical nitrogen loading, crop uptake, soil storage, vadose-zone transport, denitrification, recharge and groundwater mixing. At an individual well, nitrate concentrations are further shaped by groundwater age, flow paths, redox conditions, well depth and aquifer vulnerability (Burow et al., 2010; Castaldo et al., 2021; Kumar et al., 2020). Consequently, similar agricultural landscapes can produce markedly different nitrate outcomes, while present-day groundwater may retain the imprint of production practices from decades earlier.

This delayed and spatially heterogeneous response is not a secondary complication; it determines what groundwater observations can reveal about changes in the food system. Legacy nitrogen stored in soils, the vadose zone and aquifers can sustain nitrate delivery long after surface inputs decline, whereas recent increases—or reductions—in livestock production and fertilizer application may not yet be evident in deep or slowly recharged groundwater (Basu et al., 2022; Hansen et al., 2017; Liu et al., 2024). Groundwater monitoring therefore records the combined effects of historical source loading, transport, mixing and attenuation rather than providing a direct measure of contemporary agricultural production. Translating dietary or production scenarios into groundwater outcomes must account for this disconnect: the magnitude and timing of improvement depend not only on how agricultural nitrogen inputs change, but also on what replaces livestock production and on the hydrogeological characteristics of the receiving aquifer.

Existing studies illuminate individual parts of this pathway but rarely connect them. Field and regional studies have associated intensive animal production, manure application and cropping with elevated nitrate in groundwater and surface waters (Burkart & Stoner, 2007; Weldon & Hornbuckle, 2006; Zirkle et al., 2016). These studies establish plausible source–receptor relationships where sources and receptors are closely characterized, but they do not establish whether livestock explains national nitrate patterns

independently of fertilizer use and cropland. National susceptibility and prediction studies address a complementary question, consistently showing that nitrogen loading interacts with well depth, soil permeability, recharge and aquifer properties to determine whether contamination is expressed at a sampled well (Nolan & Hitt, 2006; Ransom et al., 2022). Food-system studies approach the pathway from the opposite direction, linking consumption to production, land use and nutrient demand. They show that coordinated dietary and production changes can reduce environmental pressures, but translating those changes into groundwater outcomes requires models that connect dietary substitution to agricultural nitrogen inputs and ultimately to nitrate occurrence at individual wells (Springmann et al., 2018; Zhan et al., 2025).

Despite this progress, three empirical gaps limit direct inference from changes in livestock production or meat consumption to groundwater improvement. First, livestock density, manure production, feed crops and fertilizer use overlap extensively across agricultural landscapes, making their independent associations difficult to distinguish at the national scale. Second, groundwater monitoring captures a hydrogeologically filtered and delayed response rather than contemporary nitrogen loading. Third, the meat sector extends beyond farms. Slaughter and further-processing facilities generate distinct waste streams and may create localized pathways that are not represented by livestock inventories. These components have rarely been evaluated together within a common national groundwater framework.

We address these gaps by asking whether livestock production retains a distinct national association with groundwater nitrate after accounting for crop-production pressures and aquifer susceptibility. We then test whether observations from 2000–2020 contain a coherent temporal signal, whether agricultural and meat-sector variables improve prediction in watersheds excluded from model training, and how predicted nitrate risk changes under alternative livestock-sector transitions. The scenarios distinguish reductions in livestock and manure pressure alone from coordinated changes in feed-crop production, cropland and nitrogen demand. Extending the analysis downstream, we distinguish slaughter establishments from further-processing facilities. If contemporary meat-sector facilities exert a localized influence detectable at the national scale, nitrate risk should vary systematically with facility proximity or pressure after surrounding agriculture and hydrogeological conditions are accounted for.

We integrated 2000–2020 groundwater observations across the conterminous United States with cattle density, cattle-manure and fertilizer nitrogen, cropland and feed-crop shares, climate, groundwater chemistry, well depth and aquifer vulnerability. The analytical sequence follows the physical chain shown in Fig. 1. We first determine whether mapped overlap survives multivariable and nonlinear adjustment. We then test whether agricultural source domains improve out-of-watershed prediction beyond hydrogeology, examine annual patterns, and use continuous scenarios to compare livestock-only and coordinated livestock–crop transitions. Finally, we evaluate current slaughter and processing geography as an exploratory downstream exposure. Our hypothesis is not that livestock has no effect. It is that its observed national groundwater signal is conditional: source pressure is shared with crop production, the aquifer filters that pressure, and modeled benefits depend on how the agricultural nitrogen system reorganizes. The study therefore tests the inferential steps between meat-sector change and groundwater response rather than estimating a causal effect of individual consumption.

2. Results and discussion

2.1 Agricultural landscapes, rather than a single nitrogen source, organize nitrate risk

The primary site-year dataset contained 30,340 observations from 14,995 wells across 3,311 HUC10 watersheds. The common complete-case sample used to compare agricultural sources comprised 19,270 well-years from 8,246 wells in 1,694 HUC10 watersheds, with a nitrate-N exceedance rate of 7.3%. Cattle-manure nitrogen and nitrate overlapped across parts of the central United States, but elevated nitrate also occurred outside counties with the greatest mapped manure intensity (Fig. 2a). The spatial pattern therefore establishes co-location.

Multivariable adjustment separated the livestock signal from the broader agricultural setting in which it occurred. Per interquartile-range increase, the fully adjusted odds ratio for cattle density was 1.37 (95% confidence interval (CI), 0.91–2.05), and that for cattle-manure nitrogen was 1.19 (95% CI, 0.87–1.63); both estimates were imprecise and compatible with the null (Supplementary Fig. S1). Cropland and feed-crop shares showed positive associations of similar magnitude but greater precision, with odds ratios of 1.40 (95% CI, 1.08–1.82) and 1.37 (95% CI, 1.06–1.76), respectively. Fertilizer nitrogen had an odds ratio of 0.80 (95% CI, 0.58–1.12). This

conditional estimate should not be interpreted as evidence of a protective effect because fertilizer, manure and land-use intensity are correlated and their relationships with nitrate are not adequately represented by simple source-by-source comparisons (Fig. 2b,c).

These results complicate the simple proposition that greater livestock pressure should translate proportionally into greater nitrate exceedance. Cattle and manure remain plausible nitrogen sources, but county-level livestock pressure is embedded within feed production, fertilizer application and regional land use. Attribution to any single component of this system is therefore sensitive to the correlated exposures and spatial controls included in the model. The more defensible inference is that groundwater nitrate is associated with the broader agricultural landscape, whereas national partitioning among individual nitrogen sources remains uncertain without temporally resolved nitrogen budgets or source-specific tracers.

The weaker national associations do not necessarily conflict with stronger relationships reported in some livestock-intensive regions. Local studies can characterize source–receptor pathways using well location and construction, groundwater-flow information, hydrochemistry and isotopic tracers, thereby constraining potential nitrate sources within a defined setting (Biddau et al., 2019; Singleton et al., 2007; Zirkle et al., 2016). National analyses instead evaluate heterogeneous agricultural and hydrogeological settings in which livestock density, manure production, fertilizer use and crop production are spatially correlated and nitrate occurrence also varies with well depth, recharge, soil properties, geology and redox conditions (Burow et al., 2010; Nolan & Hitt, 2006; Ransom et al., 2022). Differences in spatial scale, exposure definition and hydrogeological resolution may therefore contribute to differences among estimates.

The positive cropland and feed-crop estimates place the livestock question within this broader agricultural geography. Feed production connects livestock demand to fertilizer use and land allocation, but feed-crop share is not itself a livestock-specific source. Crops categorized as feed crops may also supply food, fuel and export markets, and county-level crop proportions cannot identify the nitrogen ultimately reaching an individual well. We therefore refer to these variables as crop-production and nitrogen-management factors rather than treating a “crop system” as a single exposure. Their more precisely estimated adjusted associations do not transfer responsibility from livestock to crops. Instead, they illustrate why production sectors cannot be cleanly partitioned using static national layers: livestock demand, crop production and nitrogen inputs are interconnected components of the agricultural economy, whereas nitrate transport and attenuation operate at much finer hydrological scales.

This first result establishes the problem that organizes the remainder of the analysis. Spatial overlap identifies where exposures and outcomes coexist; multivariable coefficients test whether an exposure retains a conditional association after measured covariates are considered. Neither establishes whether that relationship is nonlinear, geographically stable, transferable to unseen watersheds or how predicted nitrate risk changes under specified intervention scenarios. We addressed these questions in sequence.

2.2 Crop-production information improves spatial prediction more consistently than livestock or facility information

Incremental predictor blocks were used to assess how each information domain affected prediction when entire HUC10 watersheds were excluded from model fitting. The model containing hydrogeological and climatic predictors achieved a mean area under the receiver-operating-characteristic curve (AUROC) of 0.749, a precision–recall area under the curve (PR-AUC) of 0.221 and a Brier score of 0.0718. Adding fertilizer intensity, cropland share and feed-crop share increased AUROC to 0.772 and PR-AUC to 0.250 and reduced the Brier score to 0.0706. Among the predictor blocks evaluated, this block produced the most consistent improvement in exceedance classification.

Adding cattle density and manure nitrogen to the crop-production model did not improve the classification metrics: AUROC decreased to 0.761 and PR-AUC to 0.245. The livestock block modestly improved prediction of continuous log-transformed nitrate, increasing R^2 from 0.174 to 0.190 and reducing root-mean-square error from 0.759 to 0.753. Adding slaughter variables increased continuous-outcome R^2 to 0.195 but reduced exceedance AUROC to 0.758 and PR-AUC to 0.235. After further-processing variables were added, AUROC increased to 0.769, remaining below that of the crop-production model, while continuous-outcome R^2 decreased to 0.182. Livestock and facility variables therefore captured some variation in nitrate concentration but did not produce consistent improvements across exceedance discrimination, precision–recall performance, probability accuracy and continuous-outcome prediction. Because these models are predictive, their performance indicates the incremental information supplied by each predictor block under the specified sequence; it does not identify causal sources.

The performance changes were modest in absolute magnitude but differed in consistency across metrics. AUROC measures the ability to rank exceedance observations above non-exceedances, whereas PR-AUC focuses more directly on performance for the less common exceedance class. The Brier score evaluates the accuracy of predicted probabilities. Improvement in only one metric can therefore reflect better prediction of one aspect of the outcome without a corresponding improvement in exceedance identification or probability accuracy. The crop-production and fertilizer block improved all three classification metrics, whereas subsequent livestock and facility blocks did not do so consistently. Blocked validation evaluates whether this additional information improves prediction in watersheds excluded from training, rather than whether exposures and outcomes merely overlap spatially.

The continuous and binary outcomes address related but distinct prediction tasks. A variable may help predict variation within the predominant range of nitrate concentrations while adding little ability to identify concentrations above the 10 mg L⁻¹ nitrate-N threshold. This pattern was observed for the livestock block: continuous-outcome performance improved modestly, whereas exceedance classification did not. The result does not imply that livestock variables contain no relevant information. Rather, they contributed less consistently than crop-production variables to national exceedance prediction in held-out watersheds. Hydrogeological and climatic variables characterized variation in groundwater susceptibility, after which cropland and fertilizer information provided the largest incremental improvement among the source-related blocks evaluated.

Machine learning does not resolve source attribution on its own. Correlated predictors can substitute for one another, estimated importance depends on the variables available to the model, and geographically stable proxies can improve prediction without representing a physical mechanism. We therefore use spatially blocked prediction as a test of incremental information content, not as evidence that the most predictive variable is the source of contamination. Within that scope, the results are consistent with the regression analysis: livestock variables did not provide a stable, dominant national signal after crop-production and hydrogeological information had been included.

2.3 National nitrate exceedance did not follow a monotonic annual trend

We estimated annual models to avoid imposing a temporal pattern based on two broad study periods. Across 30,340 site-years, adjusted annual exceedance probabilities ranged from approximately 7.1% to 11.4% between 2000 and 2020 and fluctuated substantially among years. When year was modeled as a continuous term, the estimated odds ratio was 1.08 per decade (95% CI, 0.94–1.25), providing no evidence of a monotonic national increase or decrease. A repeated-well analysis restricted to 12,586 site-years from 1,906 wells sampled in at least three years spanning five or more years produced an odds ratio of 0.99 per decade (95% CI, 0.77–1.27).

Monitoring composition changed over the same period: the number of observed wells decreased from 1,961 in 2000 to 754 in 2020. The similar conclusions from the full and repeated-well analyses reduce, but do not eliminate, concern that the estimated annual variation arose from changes in sampling coverage. Neither analysis supports rapid national groundwater recovery or deterioration over the study period. The observed pattern is compatible with local changes in nitrogen loading, delayed groundwater responses and heterogeneous monitoring that do not combine into a single national trajectory.

The absence of a monotonic national trend does not imply temporal stability in every region. Annual estimates average across aquifers with different recharge regimes, land-use histories and monitoring schedules. Improvement in some areas can coexist with deterioration elsewhere, while the composition of the observed well network may change even after measured covariates are included. The repeated-well analysis partially addresses this limitation by restricting the sample to more frequently observed wells, but it does not constitute a balanced panel because wells were not necessarily sampled in the same years. Moreover, only 1,906 wells met the inclusion criteria. This analysis therefore supports the absence of a detectable monotonic trend in the available national sample but cannot resolve regional trajectories.

The temporal findings also constrain interpretation of the agricultural exposure layers. Cattle density and manure nitrogen were derived primarily from recent inventory years, whereas groundwater sampled in 2000 may contain nitrogen applied years or decades earlier. These variables should therefore be interpreted as spatial indicators of agricultural pressure rather than annual exposure estimates. Attributing year-to-year changes in groundwater nitrate to livestock, fertilizer or crop production would require temporally resolved nitrogen inputs linked to groundwater travel times and historical land use. The annual model serves a narrower purpose: it shows that dividing the record into 2000–2010 and 2011–2020 imposes a sharper temporal contrast than the annual observations support.

2.4 Livestock reductions alone produced limited modeled national change

We evaluated livestock-pressure reductions continuously from 0% to 50% in five-percentage-point increments. Models were fitted using five-fold HUC10-blocked validation, and each scenario was applied to observations in watersheds excluded from the corresponding training fold. The baseline out-of-fold exceedance probability was 7.44% across 30,340 site-years. A 25% proportional reduction in cattle density and cattle-manure nitrogen reduced predicted risk by 1.25% relative to baseline, corresponding to an absolute change of -0.093 percentage points (HUC10-bootstrap 95% interval, -0.236 to 0.049 percentage points). At a 50% reduction, predicted risk decreased by 3.73%, corresponding to an absolute change of -0.278 percentage points (95% interval, -0.477 to -0.109 percentage points; Fig. 3a).

A stylized coordinated-transition scenario additionally reduced feed-crop share, associated cropland, and fertilizer demand in proportion to the livestock reduction. Under this scenario, predicted risk decreased by 6.20% at a 25% livestock reduction and by 9.19% at a 50% reduction. The corresponding absolute changes were -0.462 percentage points (95% interval, -0.682 to -0.266) and -0.684 percentage points (95% interval, -0.961 to -0.427). Among 4,802 site-years in 454 HUC10 watersheds in the upper quintile of the combined livestock-pressure and groundwater-vulnerability score, a 50% livestock-only reduction decreased predicted risk by 6.95%, whereas the coordinated transition decreased it by 11.16% (Fig. 3b).

The contrast between the two pathways indicates that modeled groundwater outcomes depend on how crop production and nitrogen inputs are assumed to change with livestock numbers. The relatively shallow livestock-only curve reflects changes in cattle density and manure nitrogen while other agricultural predictors remain fixed. The larger coordinated-transition response results from simultaneous changes in several correlated agricultural predictors. It should therefore not be interpreted as the isolated effect of reducing livestock or as a forecast of how agricultural markets would respond.

A sensitivity scenario replaced removed manure nitrogen one-for-one with synthetic fertilizer. It produced a larger apparent decline in predicted risk because the fitted model assigned a counterintuitive conditional relationship to fertilizer nitrogen. This result is not credible as a causal policy estimate and is reported as a model diagnostic in the Supporting Information. More generally, these scenarios are conditional predictions from an observational model. They do not represent market equilibrium, farmer adaptation, land-use substitution or the delayed response of groundwater to altered nitrogen loading.

Evaluating the full reduction range avoids treating 25% and 50% as uniquely justified policy thresholds; they serve only as reference points along the modeled response curves. The increasing separation between the livestock-only and coordinated-transition curves shows that the fitted model predicts greater improvement when changes in crop-production and nitrogen-management variables accompany reductions in livestock pressure. However, because these predictors are correlated and altered according to imposed proportional rules, the difference between the curves remains conditional on the scenario design.

The magnitude of change also depends on the denominator used for reporting. The 3.73% relative reduction under the 50% livestock-only scenario corresponds to an absolute decrease of 0.278 percentage points from the baseline exceedance probability of 7.44%. The coordinated scenario produced a larger but still moderate absolute decrease of 0.684 percentage points. Predicted reductions were larger in watersheds classified as having both high livestock pressure and high groundwater vulnerability. Because livestock pressure contributed to the definition of this subgroup, the result should be interpreted as model-based effect heterogeneity within a high-exposure, high-susceptibility stratum rather than as independent validation of the underlying pathway.

The synthetic-fertilizer replacement scenario further illustrates the limits of statistical counterfactuals. Its direction was inherited from the model's unstable conditional fertilizer relationship rather than from a nitrogen mass balance. A mechanistic substitution analysis would require crop-specific nutrient demand, manure availability after storage and handling losses, fertilizer-use efficiency, yield responses, land replacement and the spatial redistribution of feed production and manure. Counterfactual predictions become policy-relevant only when the jointly altered variables describe an agriculturally and biogeochemically plausible state.

2.5 Current slaughter locations show no monotonic nitrate gradient

The facility analysis distinguished slaughter establishments from further-processing facilities. The mapped directory contained 5,872 facilities with usable coordinates in the conterminous United States: 141 slaughter-only facilities, 1,205 combined slaughter-and-processing facilities and 4,526 processing-only facilities (Fig. 4a).

After adjustment for agricultural factors, climate, well depth, aquifer vulnerability, pH, year and HUC2 basin, the estimated probability of nitrate-N exceedance was 8.1% within 0–10 km of a slaughter establishment, 9.0% at 10–25 km, 8.5% at 25–50 km, 7.4% at 50–100 km and 7.7% beyond 100 km (Fig. 4b). These estimates did not form a monotonic distance gradient. The volume-weighted

slaughter-pressure index had an odds ratio of 1.17 per interquartile-range increase (95% CI, 0.94–1.47) after full adjustment, compared with 1.64 (95% CI, 1.35–2.01) in the minimally adjusted model. Species-specific estimates were also imprecise: 1.12 for cattle/beef (95% CI, 0.92–1.36), 1.09 for poultry (95% CI, 0.89–1.33), 1.17 for swine (95% CI, 0.96–1.44) and 1.19 for sheep/goat facilities (95% CI, 0.99–1.43; Fig. 4c).

Facility variables also provided little incremental predictive information. In a separate baseline-versus-FSIS comparison, adding proximity, facility-count and volume-weighted pressure variables changed spatially blocked AUROC from 0.7676 to 0.7689, an absolute difference of 0.0013. PR-AUC decreased from 0.2473 to 0.2413, the Brier score increased from 0.07046 to 0.07061 and continuous-outcome R^2 decreased from 0.1878 to 0.1854. No species-specific predictor block improved all evaluated metrics. Thus, current slaughter geography provided little additional predictive information after agricultural and hydrogeological variables were included.

The attenuation of the slaughter-pressure estimate after full adjustment is consistent with shared agricultural geography. Slaughter facilities are connected spatially to livestock supply, transportation networks, labor availability, and water and wastewater infrastructure, and many occur in regions where feed production and manure generation are also concentrated. The minimally adjusted estimate may therefore partly reflect regional agricultural conditions rather than a facility-specific pathway. After those conditions were included, the estimate was smaller and its confidence interval included the null. Together with the non-monotonic distance pattern and negligible changes in held-out predictive performance, this result provides no consistent national evidence that proximity to a currently listed slaughter establishment identifies additional groundwater nitrate risk.

This conclusion does not imply that slaughter facilities cannot affect groundwater locally. Leakage from wastewater storage, excessive land application or inadequate wastewater management may create localized nitrate pathways. The national metrics used here cannot determine whether such a pathway existed, whether a facility was operating when the sampled groundwater was recharged, whether its wastewater was managed on-site or elsewhere, or whether a monitoring well was hydraulically connected to the relevant source area. Facility volume categories indicate relative processing scale but do not quantify nitrogen discharge. The analysis therefore addresses a narrow spatial question: whether currently listed slaughter locations exhibit a consistent national proximity pattern or provide incremental predictive information beyond surrounding agriculture and hydrogeology. Neither pattern was evident in the available data.

2.6 Groundwater benefits depend on nitrogen management and aquifer context

Taken together, the analyses address whether livestock-sector changes are associated with groundwater nitrate independently of crop production and hydrogeological context. Livestock and manure are components of the agricultural nitrogen cycle, but their national groundwater associations could not be separated reliably from correlated crop-production factors and spatial differences in groundwater susceptibility using static exposure layers. Cropland and feed-crop variables showed more consistent associations and contributed more to prediction in held-out watersheds. Annual nitrate risk did not follow a monotonic national trend, and current slaughter locations provided little incremental predictive information. In the scenario analysis, reducing cattle density and cattle-manure nitrogen alone produced a modest change in predicted national risk, whereas coordinated changes in feed production and nitrogen demand produced a larger response.

This interpretation rests on several complementary findings. Fully adjusted livestock and manure estimates were positive but imprecise, and their magnitude changed across spatial specifications and repeated-well analyses. Flexible prediction models gained their clearest improvement from fertilizer and crop-production information rather than livestock or facility variables. Finally, scenario contrasts became larger when livestock reductions were accompanied by changes in feed crops, cropland and fertilizer demand. No individual result identifies causal sources, but the overall pattern indicates that modeled groundwater outcomes depend on the wider agricultural system in which livestock production occurs.

The finding of limited improvement applies specifically to the modeled livestock-only pathway. It does not imply that manure cannot contaminate groundwater, that livestock management is unimportant or that dietary transitions lack other environmental benefits. It means that reducing cattle density and cattle-manure pressure while holding crop production and fertilizer demand constant produced only a modest reduction in predicted national nitrate exceedance. The coordinated scenario produced a larger response because several related agricultural predictors changed simultaneously. These estimates are conditional predictions from an observational model rather than forecasts of market adjustment or groundwater recovery.

The policy implication is therefore not that livestock management can be ignored. Manure storage, nutrient planning, application timing and wastewater treatment remain relevant intervention points, particularly where intensive agriculture overlies shallow or vulnerable groundwater. However, a percentage reduction in meat consumption should not be translated directly into an equivalent or immediate improvement in groundwater quality. Such an inference requires assumptions about changes in feed demand, cropland, manure availability, synthetic fertilizer use, the spatial distribution of nitrogen surplus and groundwater response times. Monitoring these intermediate changes would provide a more informative basis for groundwater policy than animal numbers or meat consumption alone.

Livestock should consequently be considered within broader agricultural nitrogen management. Manure can recycle nutrients and partly substitute for synthetic fertilizer when its application rate, timing and location correspond to crop demand. Where manure nitrogen exceeds local crop requirements, storage and redistribution constraints can produce localized surpluses and losses. Conversely, reducing animal production may not reduce total nitrogen loading if crop production persists and synthetic fertilizer replaces manure. The nitrogen balance of the receiving landscape is therefore more directly relevant to groundwater risk than livestock density, manure production or meat consumption considered separately.

Interventions also operate at different spatial scales. At farms, nutrient budgeting and application synchronized with crop demand can reduce nitrogen surpluses. In vulnerable aquifers, recharge-area protection and monitoring of shallow wells can focus attention on receptors more likely to reflect surface-derived contamination. At slaughter and processing facilities, measured discharge loads, wastewater-treatment performance and hydrogeological connectivity are more informative than geographic proximity alone. Food-system scenarios should similarly specify replacement foods, fertilizer substitution, land-use change and the location of displaced production.

Several limitations constrain these inferences. Cattle density and cattle-manure nitrogen were represented primarily by 2017 layers and cropland by a 2020 layer, preventing reconstruction of historical annual exposure. Repeated observations and changing monitoring coverage affected the national sample, although one-observation-per-well and repeated-well analyses assessed sensitivity to these features. Facilities listed in the current Food Safety and Inspection Service directory were temporally mismatched with groundwater observations, and the available discharge-permit linkage was incomplete. Well depth only approximated the sampled aquifer compartment and groundwater age, while local nitrogen sources, flow paths and attenuation processes were incompletely represented. The scenario estimates also depended on imposed proportional changes among correlated predictors and did not represent nitrogen mass balance, market responses or delayed aquifer recovery.

Future analyses could link historical county nitrogen budgets—including manure production, fertilizer application and crop nitrogen removal—to repeated-well observations using source-specific lag structures. Groundwater-age and isotope data could then test attribution in selected areas, while facility analyses could replace proximity with documented nitrogen discharges and down-gradient hydrogeological connectivity. Other groundwater constituents should be evaluated only through outcome-specific frameworks because their transport and sources differ from those of nitrate.

The evidence supports a conditional conclusion. Reducing livestock production may lower one component of agricultural nitrogen pressure, but groundwater improvement is neither automatic nor proportional to that reduction. It depends on how feed production and fertilizer use respond, where nitrogen surplus is reduced and whether the receiving aquifer is hydrologically connected to that change. Food-system and groundwater policies must therefore specify the agricultural transition pathway, not only its dietary endpoint.

3. Data and Methods

3.1 Study design and analytical framework

We conducted a national observational and predictive study of groundwater nitrate across the conterminous United States. The unit of analysis for the revised statistical workflow was the groundwater monitoring site-year. Groundwater observations collected from 1 January 2000 through 31 December 2020 were linked to county-level agricultural and climatic variables, HUC10 watershed identifiers, well characteristics, an aquifer-vulnerability surface and current meat-sector facilities. The analytical sequence was designed to distinguish four questions: whether livestock-related indicators were associated with nitrate after accounting for correlated crop production and hydrogeology; whether nitrate exceedance showed a coherent annual pattern; whether agricultural and meat-sector

predictor blocks improved prediction in watersheds not used to train the model; and how predicted risk changed under continuous, explicitly defined livestock-sector transition pathways. The study was not designed to estimate the causal effect of individual meat consumption. Static cattle, land-use, vulnerability and facility layers were interpreted as spatial exposure proxies unless a temporal dimension is stated explicitly in Table 1.

Two related nitrate outcomes were analyzed. The primary outcome was an indicator for nitrate-N concentration at or above 10 mg l⁻¹, the US drinking-water maximum contaminant level expressed as nitrogen. The secondary outcome was log(1 + nitrate-N), which retained information below and above the threshold while reducing the influence of the right-skewed concentration distribution. Association models quantified adjusted relationships, spatially blocked machine-learning models evaluated out-of-watershed predictive information, and scenario models generated conditional contrasts under prespecified changes to observed predictors. These estimands answer different questions and were not interpreted interchangeably.

3.2 Groundwater nitrate observations

Groundwater nitrate observations were compiled from the Water Quality Portal (WQP) result and station search endpoints, restricted to NWIS/USGS provider records, siteType = Well, sampleMedia = Water, and characteristicName = Nitrate. The scripted WQP extraction used a study window from 2000-01-01 through 2020-12-31 for the national dataset. California was supplemented separately using California Division of Drinking Water public-supply groundwater nitrate records.

The initial dataset of 102,648 NWIS groundwater records was filtered to 74,539 valid rows. Records missing valid sample dates, non-numeric values, or unsupported units were excluded. All retained nitrate concentrations were standardized to milligrams per liter as nitrogen (mg/L as N) using explicit conversion factors: mg/L as N was retained directly; mg/L as NO₃ (or NO₃⁻) was divided by 4.4268; ug/L as N was divided by 1000; ug/L as NO₃ (or NO₃⁻) was divided by 4426.8.

Duplicate nitrate records sharing the same site_id and sample_date were collapsed to a single sample-level observation after unit harmonization. Same-year observations at a monitoring site were summarized to one site-year value, preventing sites with frequent sampling within a year from dominating estimation. The analytical nitrate value retained in the final sample-level dataset was the median of the harmonized nitrate values within each site-date group. Quality-assurance fields retained the number of collapsed records, the minimum and maximum harmonized nitrate values, the within-group range, the set of original reported units, and a duplicate-consistency flag (single_record, unit_concordant, minor_variation, or discordant_duplicates). This quality-assurance inventory spans 21,233 monitoring sites across 1,760 counties and 4,388 HUC10 watersheds. Nitrate concentrations were standardized to milligrams per liter as nitrogen (mg/L as N).

3.3. Agricultural predictors

County cattle density was calculated from the 2017 county cattle inventory and 2020 TIGER/Line county land area as cattle heads per square kilometer. Cattle-manure nitrogen was obtained from the USGS county manure nutrient estimates; the 2017 cattle component was divided by county land area and expressed as kilograms of nitrogen per square kilometer. These variables represent related, but not identical, domains: cattle density describes animal concentration, whereas cattle-manure nitrogen incorporates estimated nitrogen generation. Because both were represented by a nationally consistent benchmark year rather than annual histories, they were treated as spatial indicators of livestock pressure across the 2000–2020 groundwater observation period.

Fertilizer nitrogen was obtained from the USGS county fertilizer series and normalized by county land area. The source provides approximate five-year anchor years through 2017. The updated cross-sectional association and prediction models used the harmonized fertilizer representation in the analysis table; lagged and prior-average versions were retained for sensitivity and legacy analyses. Cropland, corn, soybean and composite feed-crop areas were derived from the 2020 USDA Cropland Data Layer at 30-m resolution. Raster cells were summarized within county boundaries and expressed as proportions of valid county raster area. Cropland share represented the broader cultivated land base, whereas feed-crop share represented the portion assigned to the crop classes included in the feed-crop composite. These variables were included because livestock, manure, feed production and fertilizer use are geographically correlated components of the same agricultural nitrogen system.

3.4 Climate, groundwater chemistry and hydrogeology

County-year precipitation and mean air temperature were calculated from NOAA nClimGrid-Daily county area-average files for 2000–2020. Daily values were aggregated to annual summaries and linked by county and observation year. Trailing five- and ten-year

averages were additionally constructed for analyses of delayed response; the prediction workflow used the harmonized ten-year prior climate representation where specified. Climate variables were included as controls for recharge, evapotranspiration and temperature-dependent transport or reaction processes rather than as agricultural source indicators.

Well depth was obtained from NWIS station metadata. When a site contained repeated depth entries, the median valid depth was used. Water pH was assembled from Water Quality Portal/NWIS records; a site-year median was matched to the nitrate site-year when available, with a site-level median used as a fallback. Aquifer susceptibility was represented by the GWAVA domestic-well nitrate-vulnerability grid aggregated to HUC10 watersheds, with county support used where required by the linkage workflow. GWAVA is a static, areally summarized vulnerability index, not a measurement at the screened interval of an individual well. Well depth, pH and vulnerability therefore characterize the receiving groundwater setting at different levels of spatial support.

3.5 Spatial linkage and regional classification

Monitoring coordinates were assigned to 2020 TIGER/Line counties and USGS Watershed Boundary Dataset HUC10 polygons by point-in-polygon linkage. County-level agricultural and climate variables were joined through county Federal Information Processing Standards codes. HUC10 identifiers defined the spatial clustering and validation groups used throughout the updated analyses. An area-weighted county-HUC10 crosswalk was constructed from polygon intersections for aggregation and sensitivity analyses. Records without a valid HUC10 assignment were retained in the broader harmonized inventory but excluded from models that required HUC10 clustering or grouped validation.

For regional summaries, counties were assigned through a state-based crosswalk to five broad agricultural-hydrogeologic regions: Arid/Irrigated West, Corn Belt/Upper Midwest, Dairy-Great Lakes/Northeast, High Plains/Central Plains and Southeast/Humid South. These groupings were used to describe heterogeneity at an interpretable national scale and were not treated as aquifer boundaries. HUC2 fixed effects were used in models requiring a hydrologically oriented regional adjustment.

3.6 Agricultural association models

We estimated adjusted associations in the common complete-case sample using logistic regression for nitrate-N exceedance and ordinary least-squares regression for $\log(1 + \text{nitrate-N})$. Continuous exposures were scaled to an interquartile-range increase so effect sizes corresponded to a realistic contrast in the observed national distribution. Cattle density and cattle-manure nitrogen were evaluated in parallel livestock specifications because their strong spatial correlation would make a joint livestock coefficient difficult to interpret and could inflate uncertainty. Fertilizer nitrogen, cropland share and feed-crop share were included to separate livestock-related indicators from the crop-production setting in which they occur.

Models were built in prespecified stages. Minimal models included observation year and state fixed effects. Agricultural models added the alternative nitrogen and land-use variables. Fully adjusted models additionally included precipitation, temperature, log-transformed well depth, log-transformed aquifer vulnerability and pH. Sandwich standard errors were clustered by HUC10 to account for residual dependence among observations in the same watershed. Results for binary exceedance are reported as odds ratios and 95% confidence intervals per interquartile-range increase; continuous-outcome results are reported on the $\log(1 + \text{nitrate-N})$ scale. These coefficients are conditional associations and were not interpreted as causal effects.

To display exposure-response shape without imposing a single straight-line relationship, each focal agricultural exposure was also divided into quintiles and entered categorically. Adjusted probabilities were standardized over the covariate distribution of the common analysis sample, with HUC10-cluster-robust 95% confidence intervals. Restricted cubic splines with four degrees of freedom provided a complementary continuous test of overall association and departure from linearity; plotted contrasts were restricted to the 5th-95th percentile range to reduce leverage from sparse extremes. Sensitivity analyses replaced state fixed effects with HUC2 fixed effects and repeated the models after retaining only the latest observation from each well.

3.7 Annual nitrate models

Annual analyses used all 30,340 site-years from 14,995 wells. Observation year was first represented by indicator variables to estimate adjusted national probabilities for each year from 2000 through 2020. A separate specification entered year continuously and scaled it per decade to summarize the average direction of change, while recognizing that the categorical-year estimates could be non-monotonic. Models adjusted for agricultural variables, annual or lagged climate, well depth, aquifer vulnerability, pH and HUC2 fixed effects. Missing numeric covariates were replaced by the analysis-sample median and accompanied by missingness indicators so the annual sample was not restricted to complete cases; categorical regional information was imputed to its most frequent level

where needed. Confidence intervals were clustered by HUC10. Observed annual proportions and annual well counts were reported alongside adjusted estimates to reveal changes in monitoring composition.

A repeated-well sensitivity analysis was restricted to wells sampled in at least three distinct years over a span of at least five years. Regional observed trajectories were summarized within the five broad analysis regions. These analyses assessed whether the national curve reflected a coherent temporal pattern or the aggregation of changing and heterogeneous regional monitoring series. Because the principal livestock and land-use layers were static benchmarks, annual coefficients were interpreted as adjusted changes in observed groundwater nitrate rather than as annual responses to measured changes in livestock production.

3.8 Spatially blocked machine learning and incremental predictor blocks

Predictive analyses used histogram-based gradient boosting for both the binary and continuous outcomes. Numeric predictors were median imputed and supplied with missingness indicators. Categorical region was most-frequently imputed and one-hot encoded. Fixed model settings were used rather than selecting hyperparameters on the held-out folds: maximum tree depth 6, learning rate 0.05, 250 boosting iterations and minimum leaf size 40. Earlier exploratory comparisons also evaluated logistic regression and random forest, but the updated block analysis used the gradient-boosting family because it performed best under grouped validation.

Generalization was evaluated with five-fold GroupKFold cross-validation using HUC10 as the grouping variable. All observations from a watershed were assigned to the same fold, so no HUC10 contributed records to both model training and testing within a fold. This design addresses spatial leakage that would occur with a random record-level split. Predictor domains were added sequentially: hydrogeology and climate; fertilizer and crop land use; cattle and manure; slaughter proximity and pressure; and processing proximity and pressure. The incremental change after adding a block was interpreted as the out-of-watershed predictive information contributed by that domain conditional on the preceding blocks, not as a causal partition of nitrate sources.

Binary-outcome performance was summarized by the area under the receiver operating characteristic curve (AUROC), area under the precision-recall curve (PR-AUC) and Brier score. The continuous log-nitrate outcome was summarized by root-mean-square error, mean absolute error and R2. Permutation importance in the earlier model comparison used 12 permutations per feature and AUROC as the scoring metric; SHAP values were used diagnostically to inspect direction and nonlinearity. The manuscript emphasizes spatially blocked performance and incremental block contributions because full-sample importance can overstate generalizability when neighboring watersheds share exposure structure.

3.9 Continuous livestock-sector transition scenarios

Transition scenarios used the same 30,340 site-years and the same five-fold held-out-HUC10 design as the predictive analysis. Within each held-out fold, the model was trained on the other four folds, baseline predictions were generated for the held-out observations, and counterfactual predictions were generated only after modifying the held-out predictor values. Cattle density and cattle-manure nitrogen were reduced jointly from 0% to 50% in five-percentage-point increments. This continuous range replaced isolated 25% and 50% scenarios and allowed the shape and uncertainty of the modeled response to be inspected.

The livestock-only pathway reduced cattle density and cattle-manure nitrogen while holding crop area and fertilizer nitrogen fixed. The integrated livestock-crop pathway additionally reduced feed-crop share in proportion to the livestock-sector reduction, reduced total cropland by the displaced feed-crop area and reduced fertilizer nitrogen according to the feed-crop fraction of cropland. A diagnostic substitution pathway added one unit of synthetic fertilizer nitrogen for each unit of removed manure nitrogen; because this one-for-one substitution is a bookkeeping contrast rather than a measured agronomic response, it is treated as supporting analysis. Scenario estimates are conditional model contrasts. They do not represent market equilibrium, nitrogen mass balance, groundwater travel time or a causal forecast of dietary change.

Changes were summarized for the full national site-year population and for site-years in the upper fifth of a combined standardized livestock-pressure and aquifer-vulnerability score. The latter subgroup was prespecified to examine settings in which a large surface source and a susceptible receiving aquifer coincide. Relative changes were calculated against each observation's held-out baseline prediction and then aggregated. Ninety-five per cent intervals were estimated with 400 bootstrap replicates resampled at the HUC10 level, preserving within-watershed dependence.

3.10 Current slaughter and meat-processing facilities

Current establishment locations, inspection activities and establishment-wide slaughter-volume categories were obtained from the USDA Food Safety and Inspection Service (FSIS) Meat, Poultry and Egg Product Inspection Directory. Establishments were classified as slaughter only, processing only or combined slaughter and processing. Slaughter indicators were constructed separately for cattle/beef, poultry, swine and sheep/goat. Processing indicators distinguished ready-to-eat, not-ready-to-eat, raw-intact and raw-non-intact activities. The FSIS slaughter-volume field reports an ordinal establishment-wide category for the preceding 360 days. It was therefore used as a relative facility-size weight and was not interpreted as a species-specific head count when an establishment handled multiple species.

For each monitoring well, facility exposure was represented by distance to the nearest current slaughter establishment, establishment counts within fixed radial buffers and distance-decayed pressure indices. Pressure weights declined exponentially with a 25-km bandwidth and were truncated at 100 km; volume-weighted versions incorporated the ordinal FSIS size category. Species-specific slaughter and activity-specific processing indices were calculated separately. Distance categories of 0–10, 10–25, 25–50, 50–100 and more than 100 km were used to test whether adjusted nitrate probability showed a monotonic proximity gradient.

Facility association models adjusted for observation year, HUC2 fixed effects, cattle density, cattle-manure and fertilizer nitrogen, cropland and feed-crop shares, precipitation, temperature, well depth, aquifer vulnerability and pH. Effect estimates for pressure indices were scaled to an interquartile-range increase and confidence intervals were clustered by HUC10. Sensitivity analyses were restricted to observations from 2015–2020 and to the latest observation from each well. Facility predictors were also added as the final blocks in the spatially grouped prediction analysis. Because the directory describes current establishments and does not establish whether a facility operated throughout 2000–2020, these analyses are spatial screens for localized association and incremental prediction, not historical exposure or causal-effect estimates.

3.11 FSIS-EPA wastewater-permit linkage

To investigate whether current FSIS establishments could be connected to regulated wastewater records, facilities were matched to US Environmental Protection Agency Enforcement and Compliance History Online Clean Water Act/National Pollutant Discharge Elimination System records for animal slaughtering and processing. Candidate matches were blocked by state and scored using normalized facility name, street address, city, ZIP code and geographic-coordinate similarity. A one-to-one greedy assignment retained high- and moderate-confidence matches, with match class stored for audit. Permit issue or record dates were treated as permit-administration dates and not as facility-opening dates. Moderate-confidence links require manual confirmation. Because discharge-monitoring coverage was incomplete and heterogeneous, effluent measurements were not used to estimate nitrate effects in the present analysis.

3.12 Statistical uncertainty, software and interpretation

All confidence intervals were two-sided 95% intervals. Regression intervals used HUC10-cluster-robust covariance estimates, and scenario intervals used HUC10-cluster bootstrap resampling. Models were implemented in Python 3.12.2 using NumPy 1.26.4, pandas and GeoPandas for data processing and spatial linkage, scikit-learn 1.4.2 for grouped prediction, and statsmodels for regression. Matplotlib 3.10.0 was used for figures and SHAP 0.50.0 for diagnostic interpretation. No statistical model was treated as evidence that livestock or meat facilities have no local effects; null or imprecise national estimates were interpreted as a lack of a stable independent national association under the measured covariates and spatial-temporal support.

Table 1
Datasets and variables used in the conterminous United States groundwater nitrate risk analysis.

Dataset or layer	Source	Domain	Spatial scale	Temporal scale	Variables used	Final unit(s)
Groundwater nitrate observations (national)	Water Quality Portal, restricted to NWIS/USGS records	Groundwater quality	Well point	Sample date; observations queried for 2000–2020	Nitrate concentration as N, nitrate exceedance indicator, site identifier, coordinates, well depth, site metadata	mg/L as N; binary exceedance (0/1)
Groundwater nitrate observations (California supplement)	California Division of Drinking Water public-supply groundwater records	Groundwater quality	Well point	Sample date; 2020 subset used in augmented analysis	Nitrate concentration as N, nitrate exceedance indicator, coordinates, county and HUC linkage	mg/L as N; binary exceedance (0/1)
County cattle inventory	County cattle table assembled from All cattle - Number of heads.csv	Livestock production	County	2017 snapshot	Total cattle heads, cattle density	heads; heads/km ²
County manure nitrogen	USGS county manure nutrient estimates assembled from N-P_from_manure_1950-2017-july23-2020.csv	Livestock waste / nitrogen input	County	2017 snapshot used in analysis	Cattle manure nitrogen load, total manure nitrogen load, cattle manure nitrogen intensity	kg N; kg N/km ²
County fertilizer nitrogen	USGS county fertilizer nutrient estimates from N-P_from_fertilizer_1950-2017-july23-2020.xlsx	Agricultural nitrogen input	County	Approximate 5-year anchor years, 1950–2017	Fertilizer nitrogen load, fertilizer nitrogen intensity	kg N; kg N/km ²
County land area	2020 TIGER/Line county shapefile (ALAND)	Spatial support	County	Static	Land area denominator used to compute density and intensity metrics	km ²
Cropland and crop shares	USDA Cropland Data Layer, aggregated to counties	Land use	30 m raster summarized to county	2020 snapshot in current build	Cropland share, corn share, soybean share, feed-crop share	proportion
County climate panel	NOAA nClimGrid-Daily county area-averaged data	Climate	County	Annual summaries, 2000–2020	Mean annual precipitation, mean annual temperature	mm/year; °C
Lagged climate panel	Derived from annual county climate summaries	Climate	County	Trailing 5-year and 10-year averages	Prior 5-year and prior 10-year precipitation and temperature averages	mm/year; °C
Lagged fertilizer panel	Derived from county fertilizer table	Agricultural nitrogen input	County	Contemporaneous and lagged values	Lagged and prior-average fertilizer	ln(1 + kg N/km ²)

Dataset or layer	Source	Domain	Spatial scale	Temporal scale	Variables used	Final unit(s)
					intensity metrics	
pH companion chemistry	Water Quality Portal / NWIS pH records	Groundwater chemistry	Well point	Site-year median with site-level fallback	pH, pH join method	pH units
HUC10 watershed boundaries	USGS Watershed Boundary Dataset (WBDHU10)	Hydrographic framework	HUC10 polygon	Static	HUC10 identifier, watershed assignment	HUC10 code
County-HUC10 crosswalk	Derived from county polygons and HUC10 polygons	Spatial linkage	County-HUC10 overlap	Static	Area-overlap weights used for aggregation and sensitivity analyses	unitless weight; km ² overlap
Aquifer vulnerability surface	GWAVA domestic-well nitrate vulnerability grid, aggregated to HUC10 and county	Hydrogeological vulnerability	Grid aggregated to HUC10, with county fallback	Static	Aquifer vulnerability proxy	unitless index
Broad analysis regions	Internal state-to-region crosswalk	Regional classification	County/state assignment	Static	Region class	categorical

Declarations

Data availability

The authors declare [NEED INPUT].

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Figures

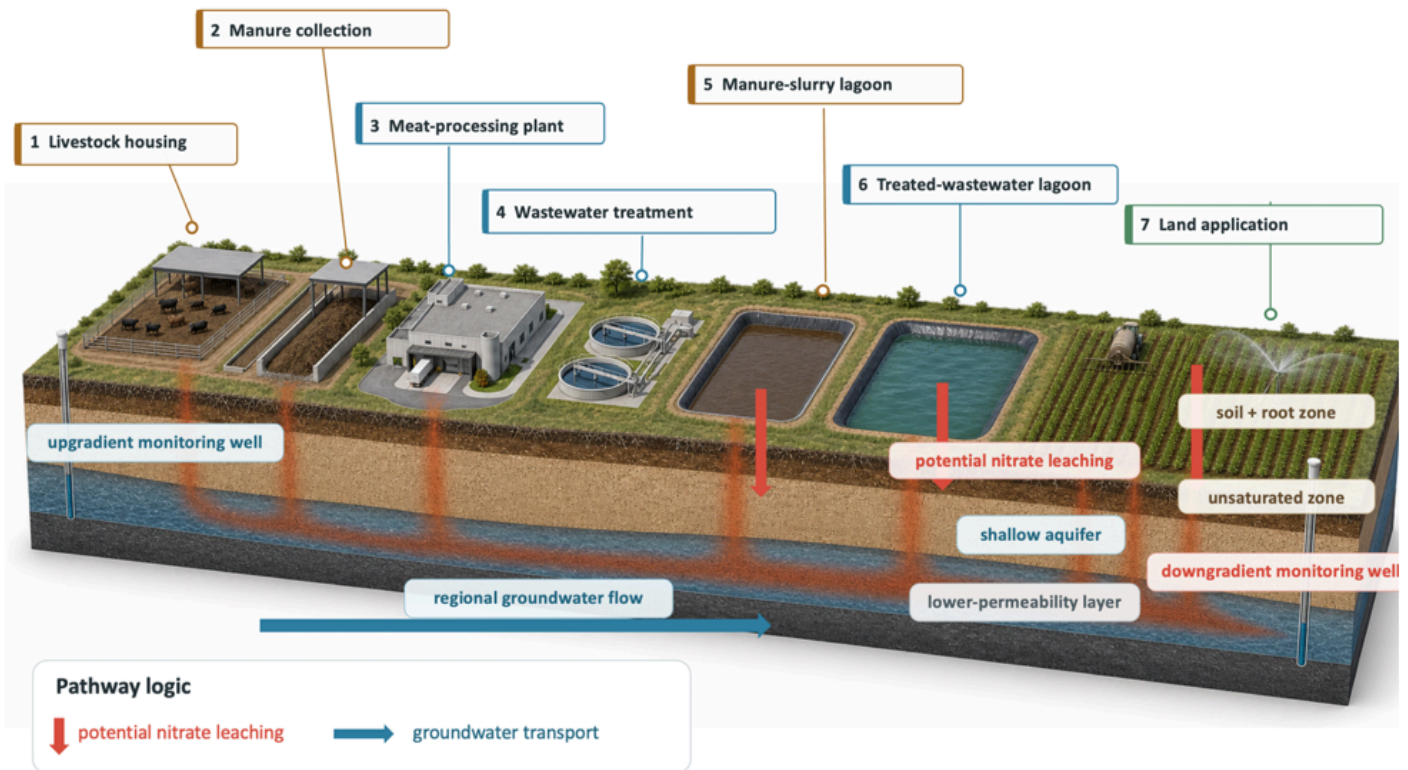


Figure 1

Conceptual pathways linking livestock production and meat processing to groundwater nitrate. Nitrogen may enter the subsurface through multiple pathways associated with livestock production, manure management, meat-processing wastewater, storage systems and land application. Organic nitrogen and ammonium (NH_4^+) released from manure or wastewater can undergo mineralization and nitrification in oxic soils and the unsaturated zone, producing nitrate (NO_3^-), which is highly mobile and may leach toward shallow groundwater. Potential source pathways include accumulation of manure in animal-housing and collection areas, seepage from manure/slurry or treated-wastewater storage where containment is inadequate, and nitrogen application exceeding crop uptake. Once nitrate reaches groundwater, advection and dispersion can transport it downgradient, while biogeochemical processes such as denitrification may provide attenuation under suitable reducing conditions. Effective wastewater treatment, maintained containment, nutrient-management practices and groundwater monitoring can interrupt these pathways. Red arrows indicate potential nitrate leaching and blue arrows indicate groundwater transport.

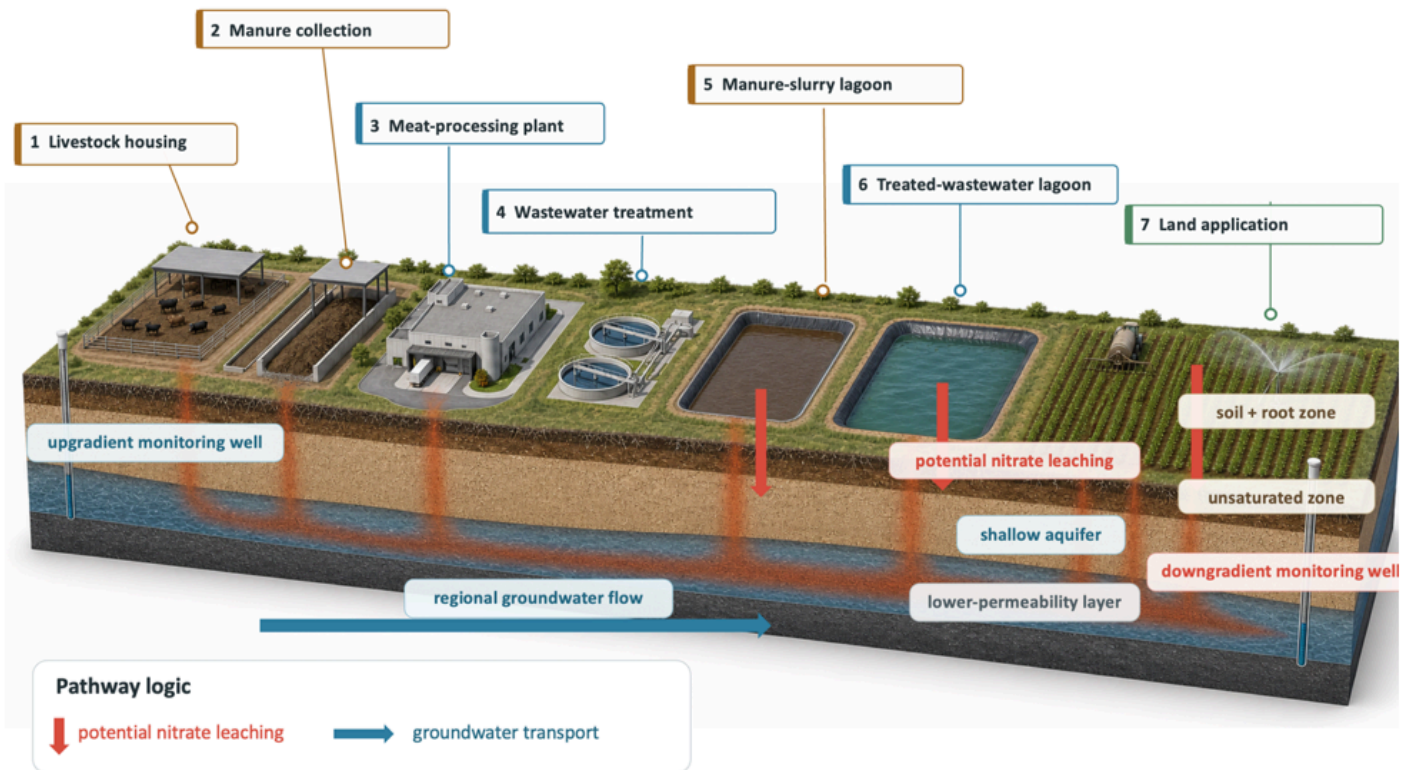


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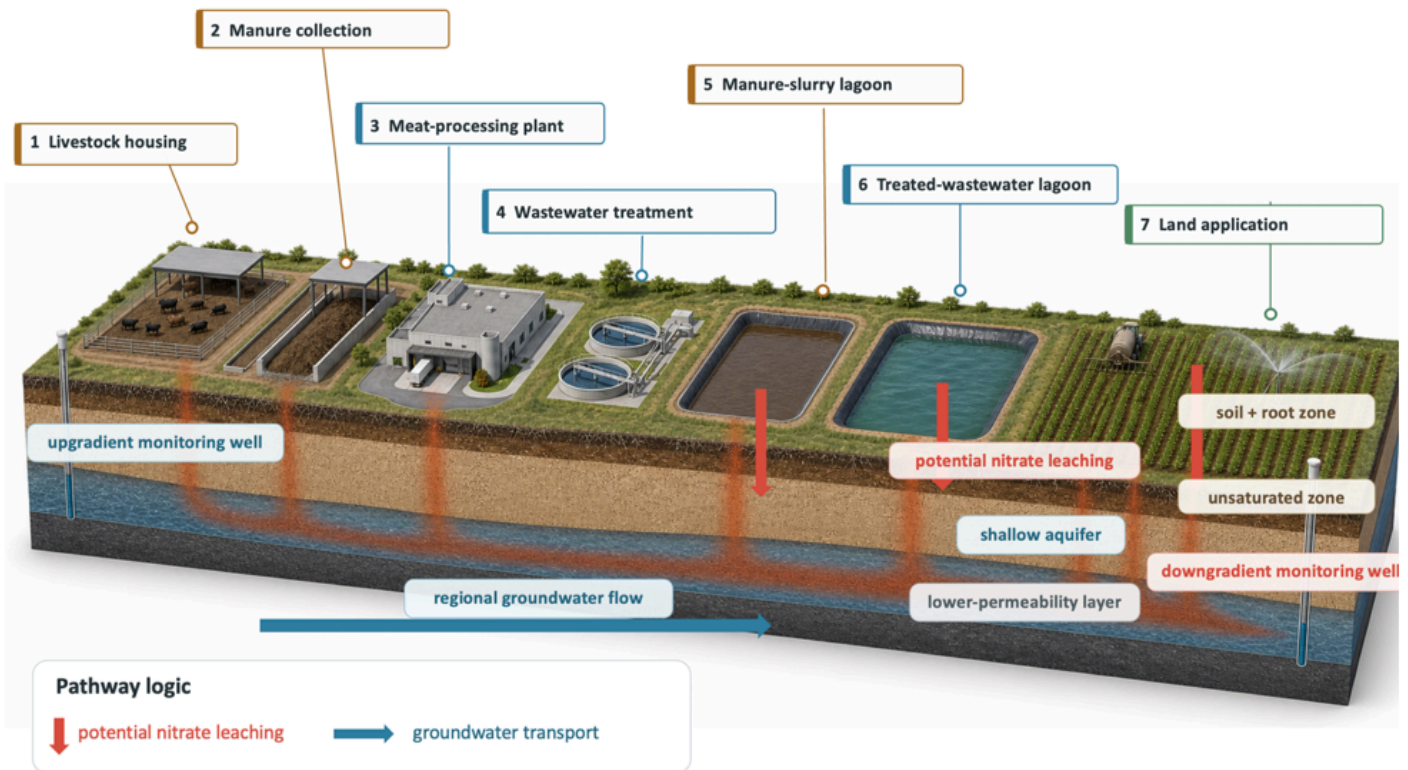


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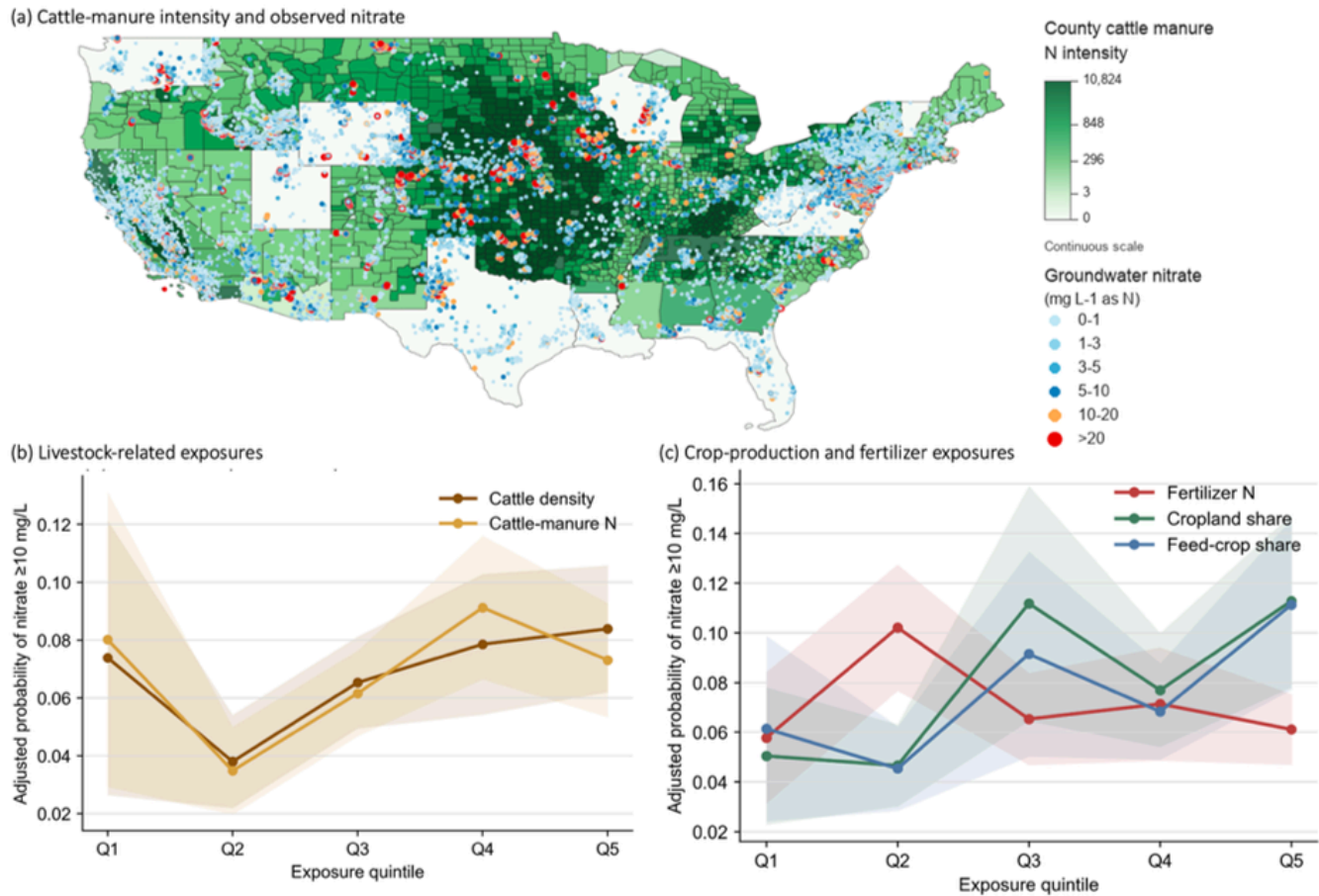


Figure 2

Agricultural nitrogen sources and groundwater nitrate exceedance. (a) Spatial distribution of county-level cattle-manure nitrogen intensity and groundwater nitrate concentrations across the contiguous United States. County shading represents cattle-manure nitrogen intensity, while monitoring-well symbols represent median nitrate-N concentrations classified as 0–1, 1–3, 3–5, 5–10, 10–20 and >20 mg L⁻¹. (b) Model-adjusted probability of nitrate-N exceedance across quintiles of cattle density and cattle-manure nitrogen intensity. Points represent adjusted probabilities and shaded areas represent 95% confidence intervals. (c) Model-adjusted probability of nitrate-N exceedance across quintiles of fertilizer nitrogen intensity, cropland share and feed-crop share. Agricultural exposure–response patterns are nonlinear and differ among nitrogen sources.

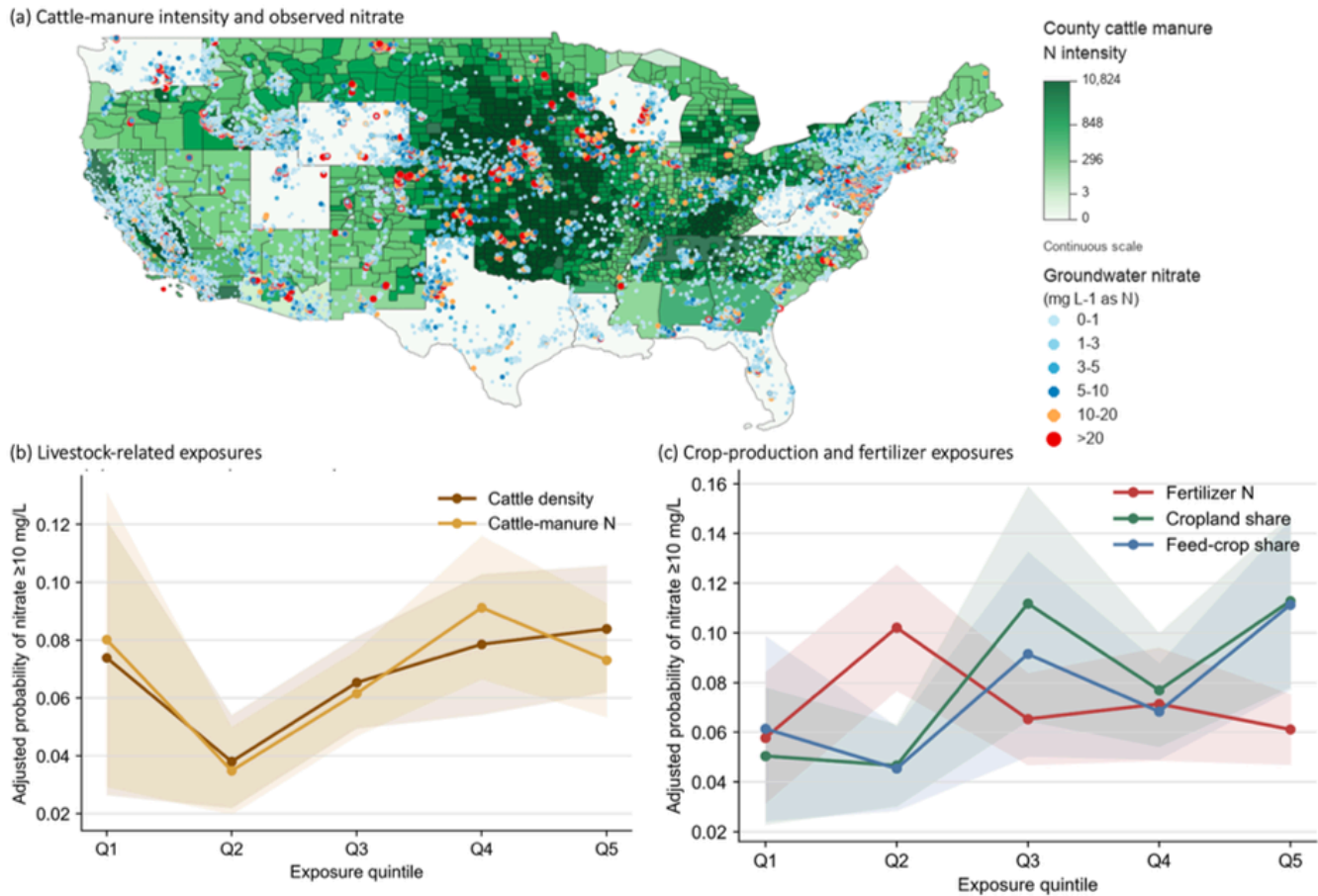


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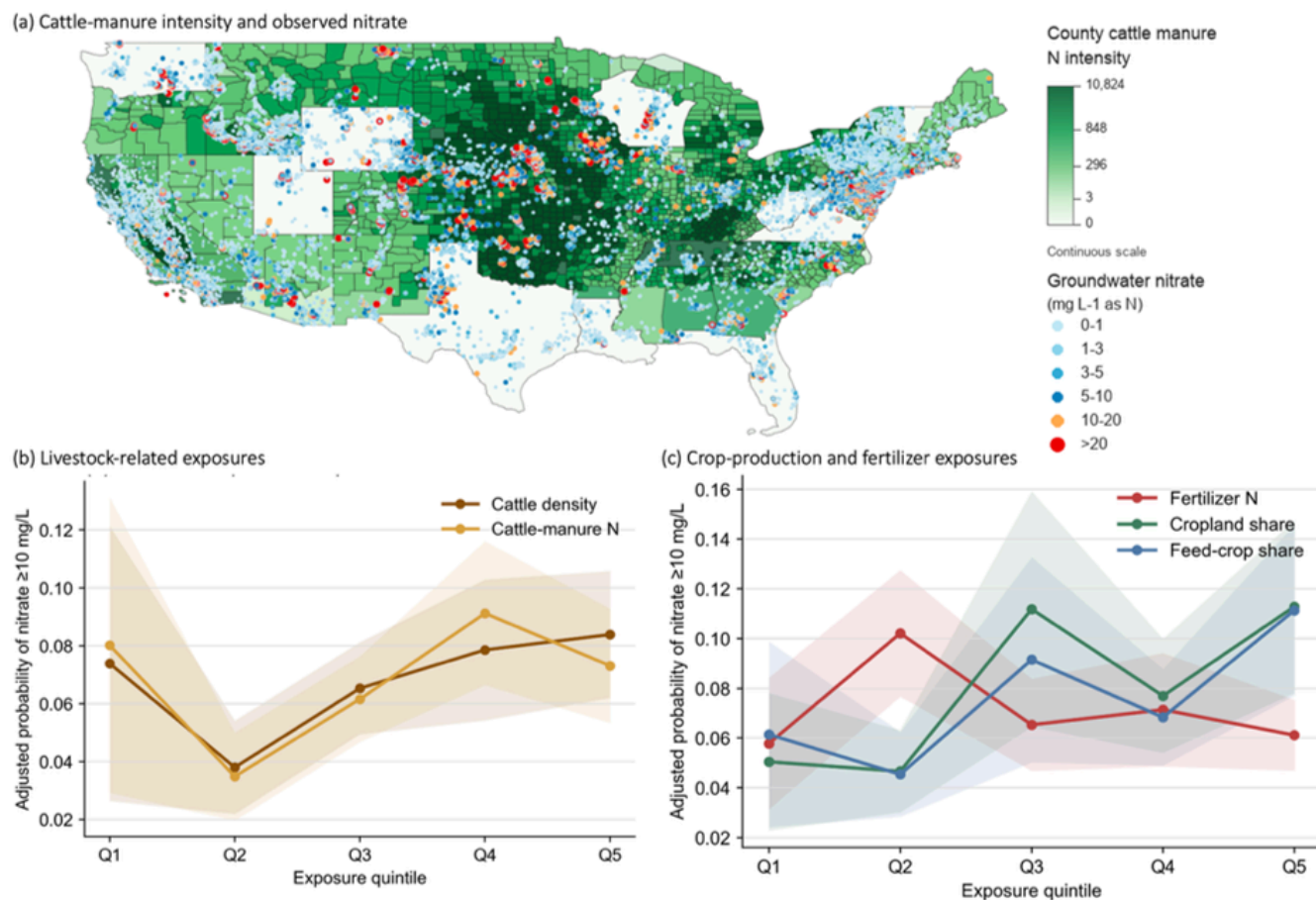


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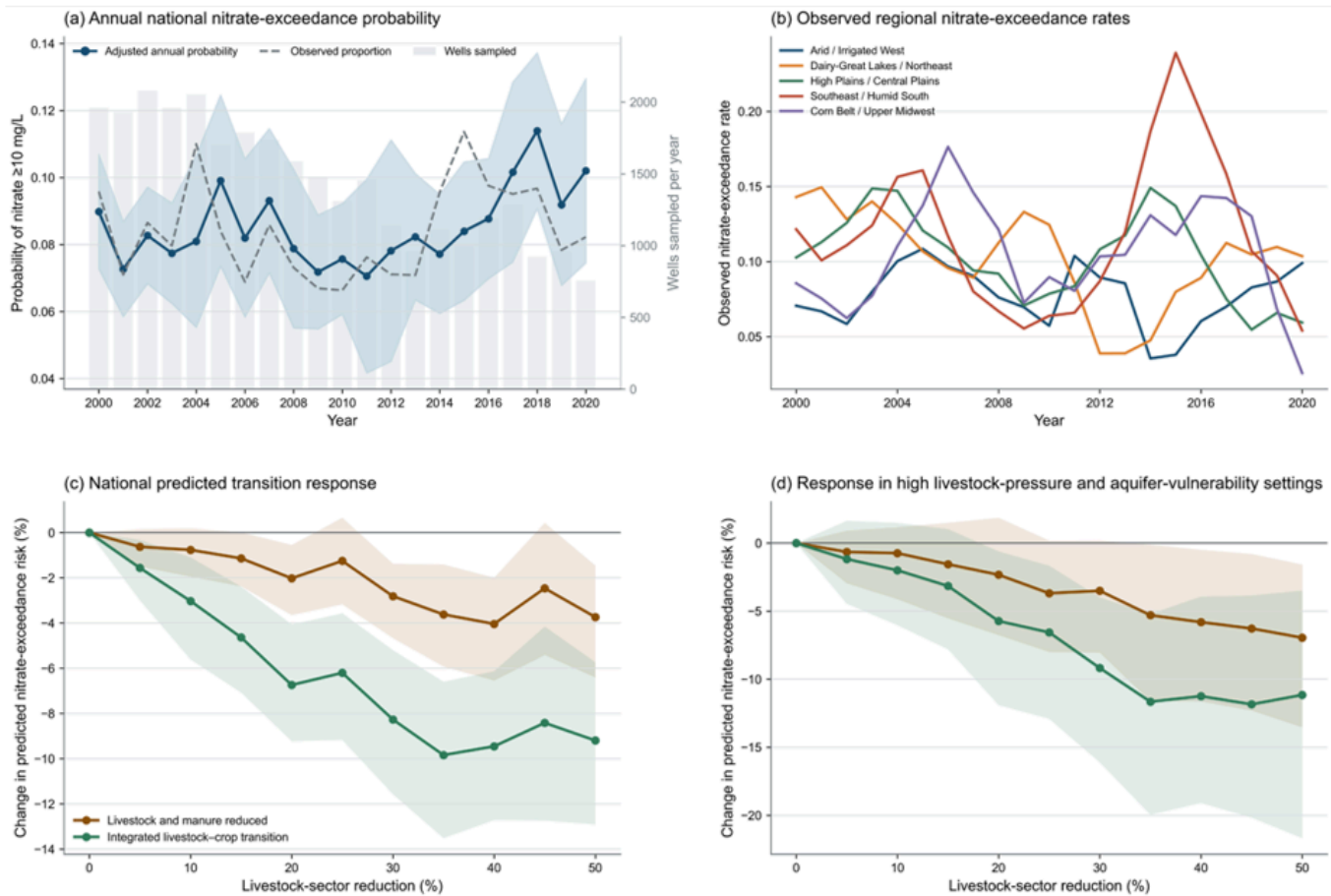


Figure 3

Temporal and spatial patterns of groundwater nitrate exceedance in the contiguous United States. (a) National annual probability of groundwater nitrate concentrations ≥ 10 mg/L from 2000 to 2020. The solid line and points show model-adjusted annual probabilities, the shaded band shows 95% confidence intervals, and the dashed line shows the unadjusted observed proportion. (b) Three-year rolling observed nitrate-exceedance rates for the five regions with the greatest sampling coverage. Regional trajectories demonstrate substantial geographic heterogeneity that is obscured by the national average. (c) Relative change in predicted national nitrate-N exceedance risk across continuous livestock-sector reductions from 0% to 50%. The livestock-only pathway proportionally reduces cattle density and cattle-manure nitrogen while holding crop-production variables constant. The integrated livestock-crop pathway also reduces feed-crop area, associated cropland and fertilizer demand. Estimates are out-of-HUC10 model contrasts for 30,340 site-years from 14,995 wells; shaded bands show HUC10-cluster bootstrap 95% intervals. (d) Corresponding predicted changes among 4,802 site-years in 454 HUC10 watersheds in the upper fifth of a combined livestock-pressure and aquifer-vulnerability score. Curves compare the livestock-only and integrated livestock-crop pathways. Lines represent out-of-HUC10 model contrasts, and shaded bands show HUC10-cluster bootstrap 95% intervals. Estimates in both panels are conditional predictions, not causal or market-equilibrium forecasts.

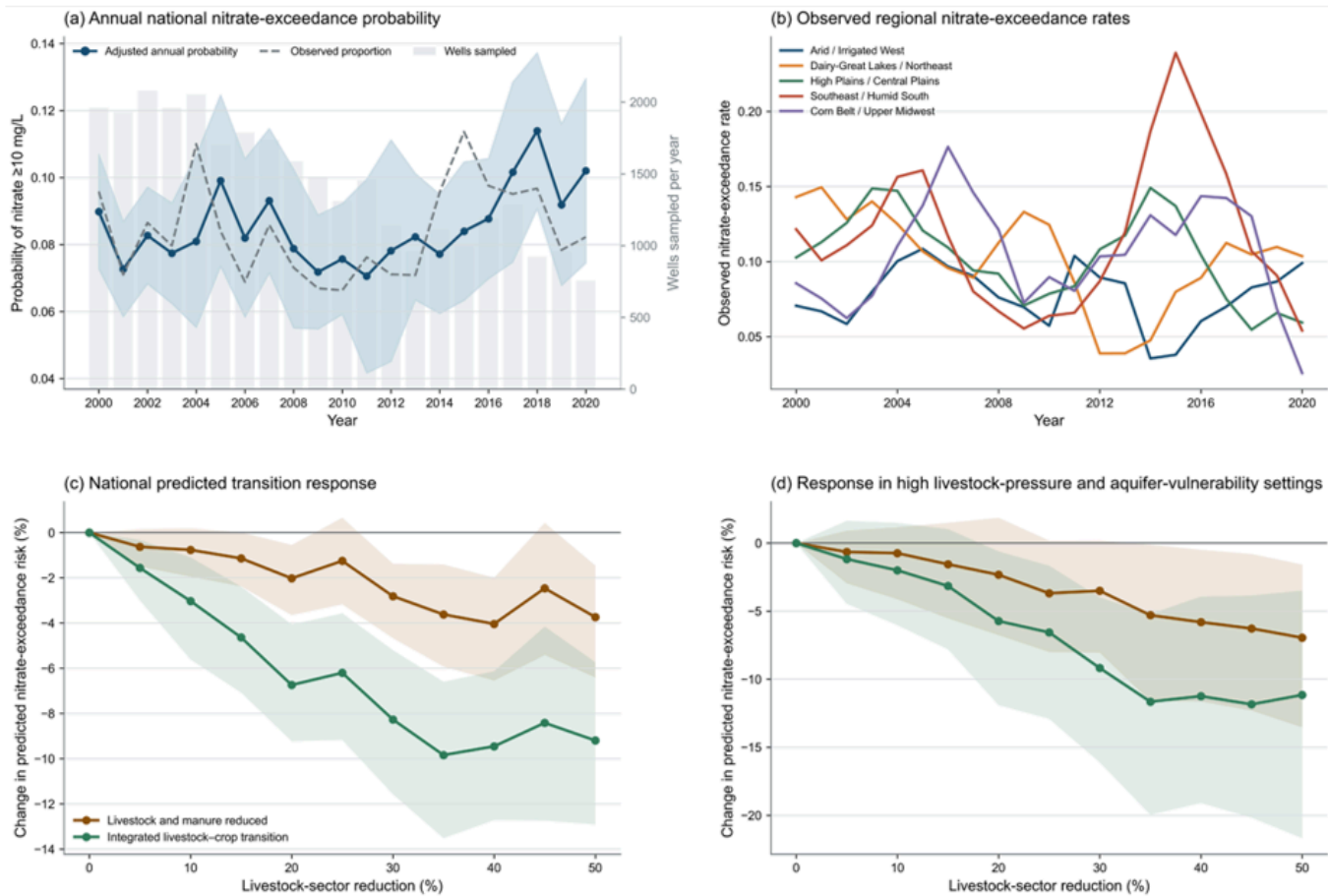


Figure 3

Temporal and spatial patterns of groundwater nitrate exceedance in the contiguous United States. (a) National annual probability of groundwater nitrate concentrations ≥ 10 mg/L from 2000 to 2020. The solid line and points show model-adjusted annual probabilities, the shaded band shows 95% confidence intervals, and the dashed line shows the unadjusted observed proportion. (b) Three-year rolling observed nitrate-exceedance rates for the five regions with the greatest sampling coverage. Regional trajectories demonstrate substantial geographic heterogeneity that is obscured by the national average. (c) Relative change in predicted national nitrate-N exceedance risk across continuous livestock-sector reductions from 0% to 50%. The livestock-only pathway proportionally reduces cattle density and cattle-manure nitrogen while holding crop-production variables constant. The integrated livestock-crop pathway also reduces feed-crop area, associated cropland and fertilizer demand. Estimates are out-of-HUC10 model contrasts for 30,340 site-years from 14,995 wells; shaded bands show HUC10-cluster bootstrap 95% intervals. (d) Corresponding predicted changes among 4,802 site-years in 454 HUC10 watersheds in the upper fifth of a combined livestock-pressure and aquifer-vulnerability score. Curves compare the livestock-only and integrated livestock-crop pathways. Lines represent out-of-HUC10 model contrasts, and shaded bands show HUC10-cluster bootstrap 95% intervals. Estimates in both panels are conditional predictions, not causal or market-equilibrium forecasts.

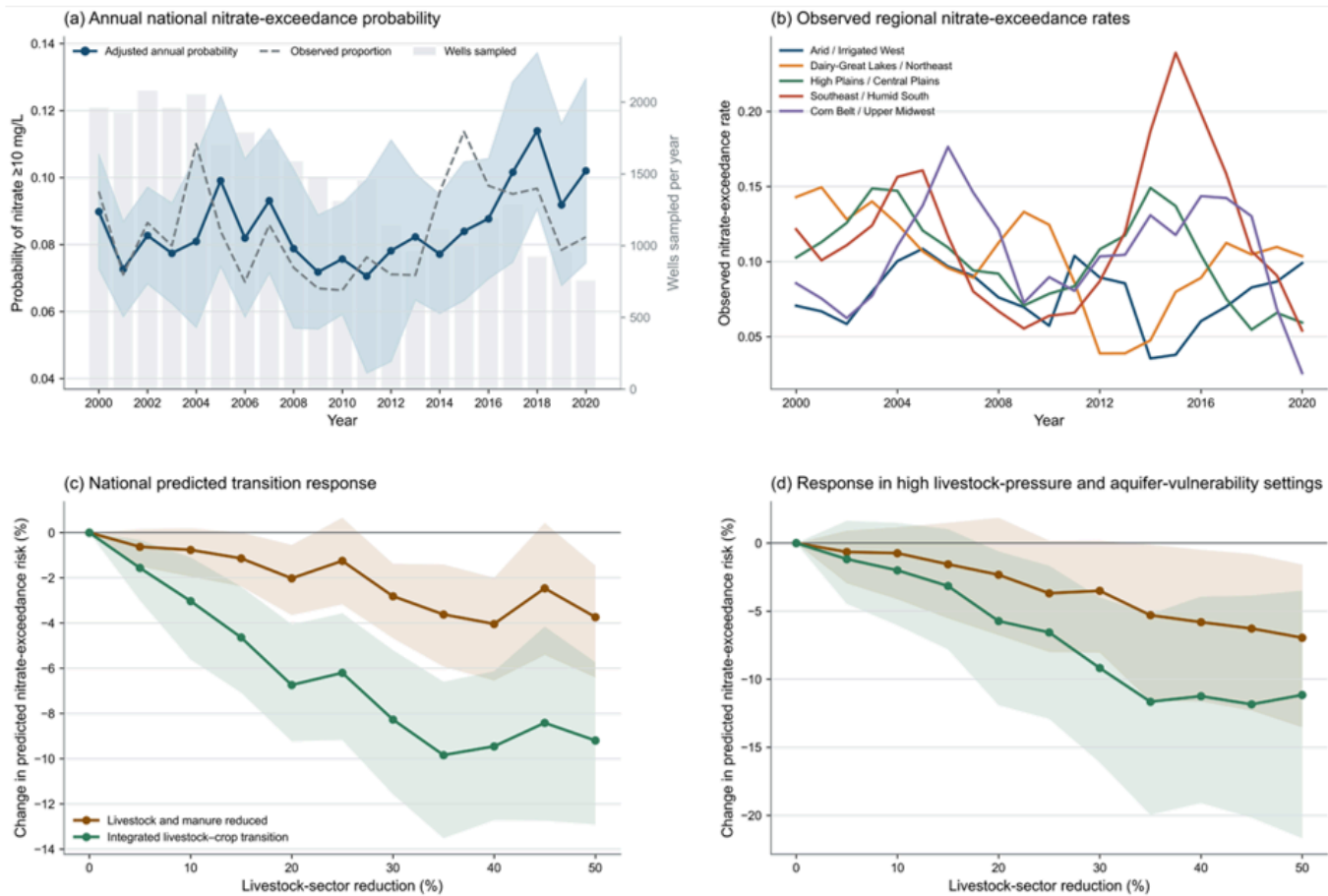


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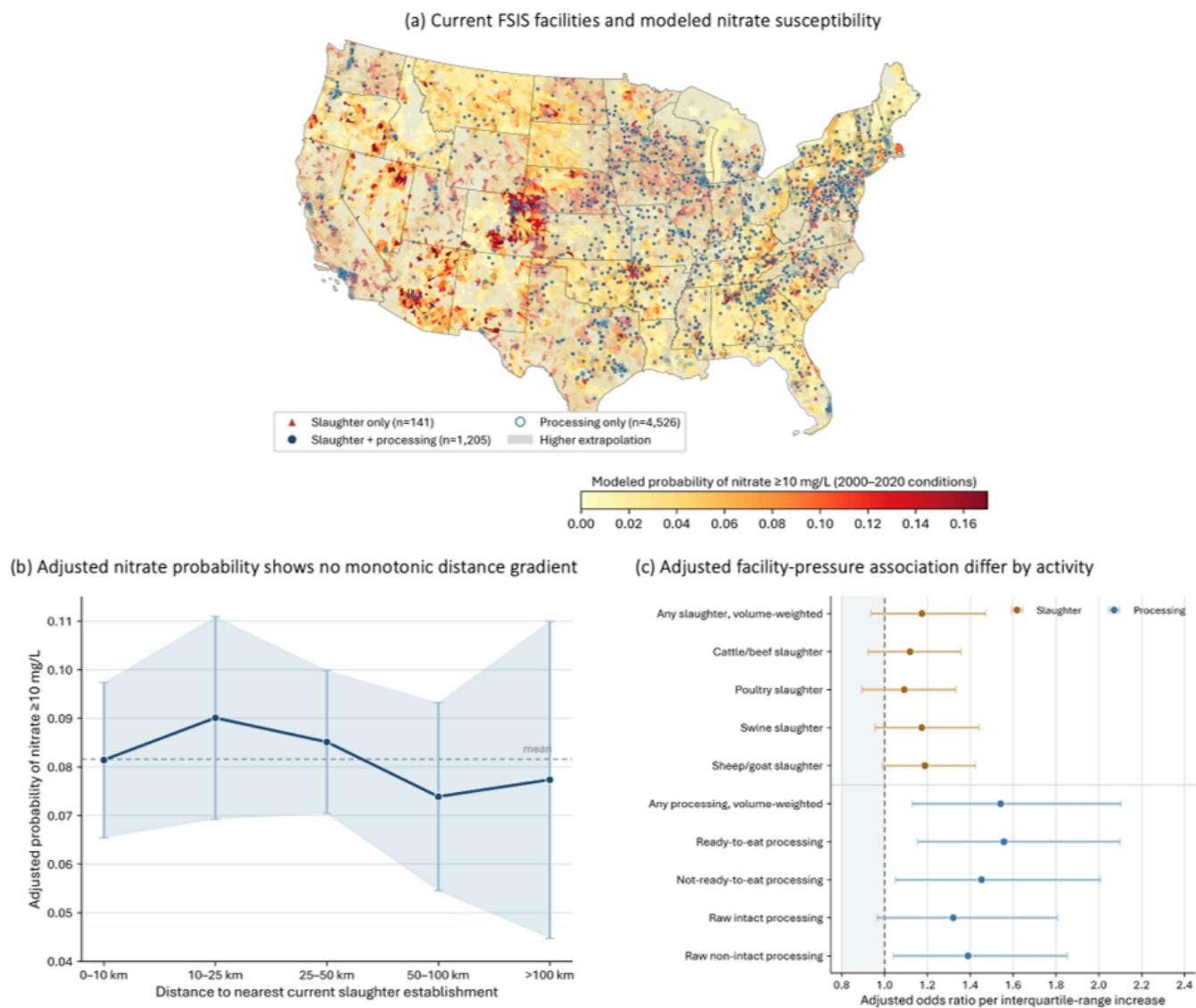


Figure 4

Associations between meat-production facilities and groundwater nitrate susceptibility. (a) Locations of current USDA Food Safety and Inspection Service (FSIS) establishments over modeled groundwater nitrate susceptibility under representative 2000–2020 conditions. Symbols distinguish slaughter-only establishments, combined slaughter-and-processing establishments and processing-only establishments; gray areas indicate locations requiring greater model extrapolation. (b) Model-adjusted probability of groundwater nitrate concentrations ≥ 10 mg L⁻¹ across categories of distance to the nearest current slaughter establishment. Points represent adjusted probabilities, vertical intervals represent 95% confidence intervals, and the dashed horizontal line denotes the overall adjusted mean. The estimates do not demonstrate a monotonic distance gradient. (c) Multivariable-adjusted associations between nitrate exceedance and volume-weighted facility pressure for overall slaughter activity, species-specific slaughter activity and major processing categories. Points represent adjusted odds ratios per interquartile-range increase in facility pressure, horizontal lines represent 95% confidence intervals, and the vertical dashed line denotes the null value of 1.0.

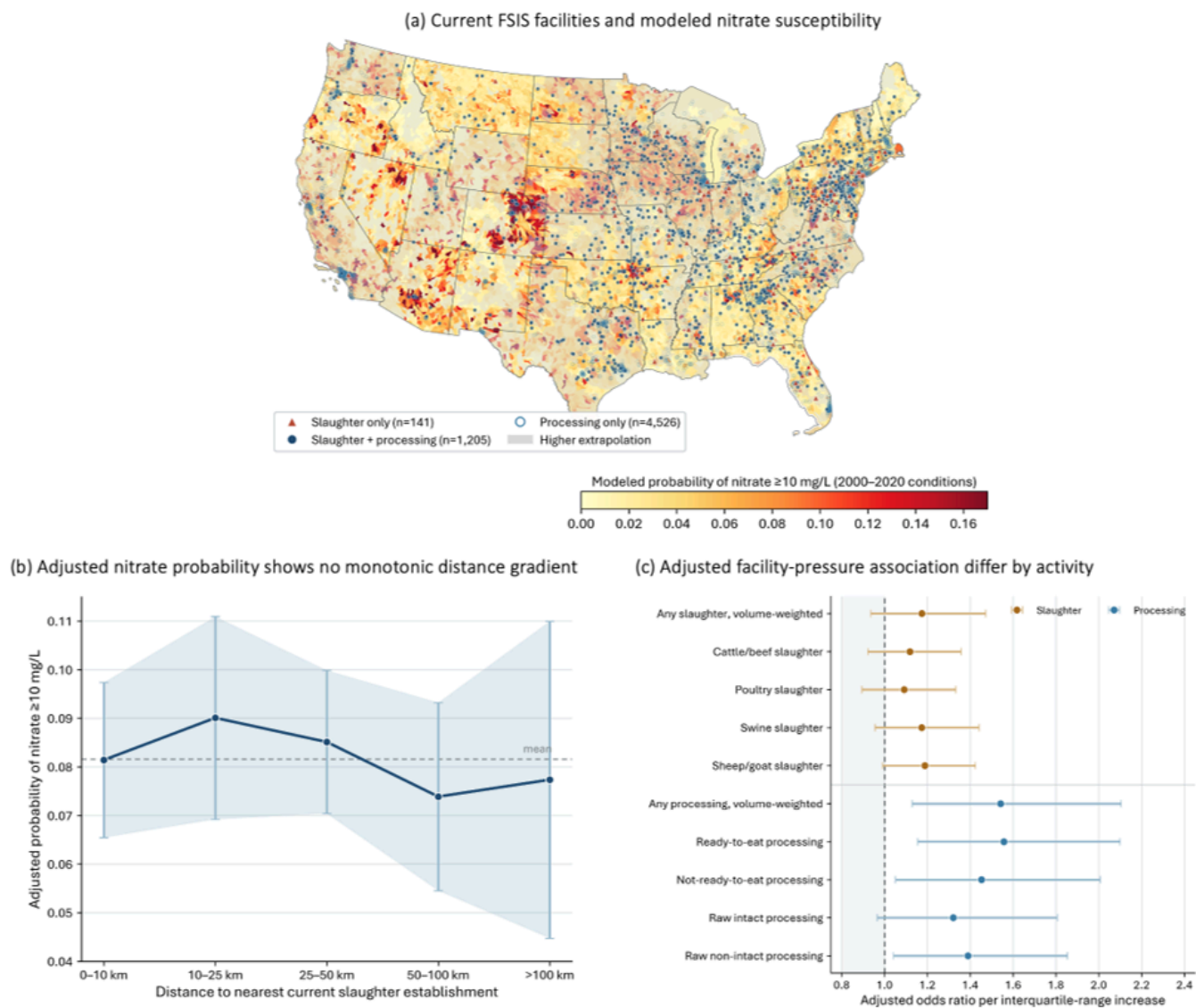


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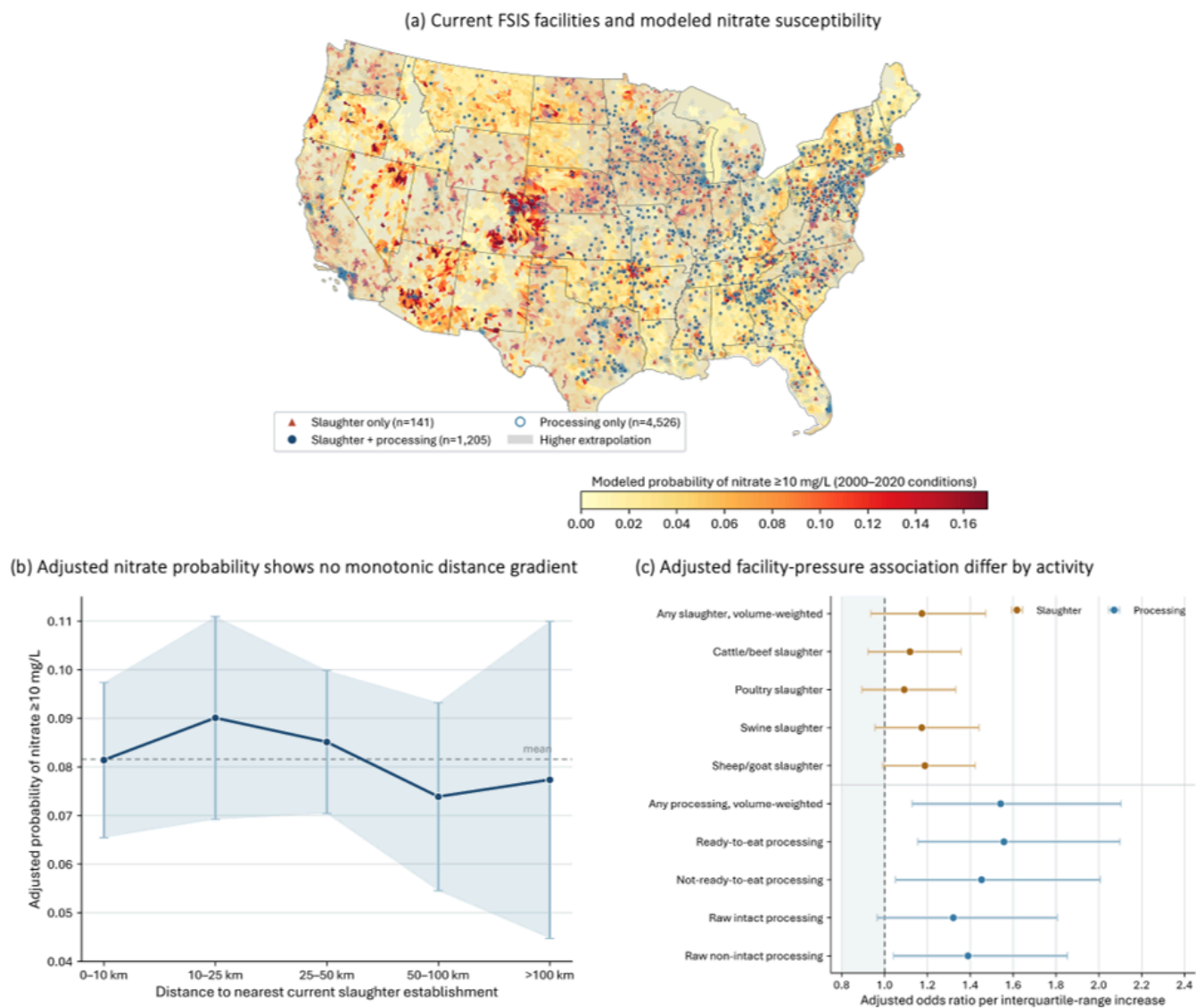


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