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Ecological sustainability challenges of large data centers: Environmental pressures, resource depletion, and sustainable digital infrastructure

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Abstract

Large, energy-intensive data centers are expanding quickly as cloud computing, cryptocurrency mining, and artificial intelligence demand more computing power. That growth creates ecological risks that extend beyond electricity use and carbon emissions. Fossil-fuel electricity and on-site diesel generators release pollutants that degrade air quality and contribute to acid deposition; water-intensive cooling reduces freshwater availability and can stress aquatic habitats; continuous cooling noise affects nearby communities and may disturb wildlife; and hyperscale campuses convert land, fragment habitat, and intensify urban heat. Institutional analyses project that the annual public health burden of air pollution associated with United States data centers could approach US$20 billion by 2030, while direct water use is already estimated at more than 100 billion gallons a year. These burdens fall unevenly on ecologically vulnerable and socially disadvantaged communities, raising questions of sustainability justice. This article examines data center impacts through an ecological sustainability lens, drawing on environmental health, freshwater ecology, acoustic ecology, land-use science, and environmental justice research. It proposes a socio-ecological framework that links five interacting impact pathways, maps them onto the planetary boundaries, and grades the evidence behind each claim, separating established findings from modeled projections and untested hypotheses. It weighs these costs against the benefits of digital infrastructure, identifies research gaps, and sets out policy priorities for aligning data center growth with planetary limits and more equitable outcomes.

Keywords: Data centers; Ecological sustainability; Acoustic ecology; Habitat fragmentation; Environmental justice; Artificial intelligence; Carbon capture; Sustainable digital infrastructure

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1. Introduction

Large-scale data centers now support much of the digital economy, including cloud services, streaming media, cryptocurrency networks, and the growing computational demands of artificial intelligence. Their footprint is expanding rapidly, with the United States (U.S.) hosting thousands of facilities and major new hyperscale campuses planned across many regions.[1] This growth is creating ecological pressures that sustainability researchers have only recently begun to examine as connected system-level problems.

Scholarship and policy debate have often treated data center sustainability as a question of energy consumption and carbon footprints. Recent work has broadened that

view to include atmospheric emissions, water depletion, noise pollution, land-use change, and social vulnerability. Tao and Gao[1] describe global data center expansion as an emerging environmental health issue and call for empirical research to quantify associated outcomes. Gour *et al.*[2] assess impacts in Virginia's Data Center Alley, one of the world's densest data center hubs, and identify several pathways through which these facilities can harm ecosystems and nearby communities. Ngata *et al.*,[3] using a mixed-methods study of Northern Virginia communities, similarly shift attention from aggregate energy use to local health impacts, water use, noise, infrastructure strain, economic burden, and power relations between host communities and beneficiaries of digital growth. Lifset *et al.*[4] frame these issues as local environmental impacts of data center proliferation, with particular attention to electric-grid strain, new transmission infrastructure, continued fossil-fuel generation, and ratepayer burdens in Virginia and nearby states. The Federation of American Scientists[5] and Environmental Health Project[6] summarize emerging concerns about air pollution, diesel backup generation, water demand, and community exposure, while emphasizing the need for stronger reporting and independent assessment.

The scale of the challenge is substantial and growing. The International Energy Agency (IEA)[7] projects that global electricity demand from data centers will reach approximately 945 terawatt-hours by 2030. Hankendi *et al.*[8] warn that data centers could consume as much as 9% of global electricity demand by 2030, yet the lack of operational data transparency from facility operators severely constrains the research community's ability to develop effective mitigation strategies.

These trajectories cannot be understood solely through the lens of carbon accounting. From a sustainability science perspective, data centers simultaneously stress multiple planetary boundaries: the climate system through greenhouse gas emissions; the freshwater cycle through enormous withdrawals; biogeochemical flows through nitrogen oxide (NO_x) and sulfur dioxide (SO_2) emissions that disrupt nutrient cycles; and biosphere integrity through land conversion and habitat fragmentation. The concept of planetary boundaries, as articulated by Rockström *et al.*[9] and updated by Richardson *et al.*,[10] provides a powerful framework for understanding why data center impacts cannot be evaluated in isolation. When a single class of infrastructure simultaneously pressures atmospheric, hydrological, and terrestrial systems, its aggregate ecological footprint may exceed what any single-pathway analysis would suggest.

This article examines the sustainability challenge of data centers through an ecological lens. Instead of treating air pollution, water use, noise, and land conversion as separate issues, it analyzes them as connected dimensions of one socio-ecological disturbance. Drawing on environmental health, freshwater ecology, acoustic ecology, land-use science, and environmental justice literatures, it proposes a conceptual framework organized around five principal impact pathways, reviews the evidence in each domain, identifies research gaps, and outlines policy priorities for keeping digital infrastructure development compatible with ecological integrity and equitable outcomes. To make that synthesis usable, the article grades the strength of evidence behind each claim, maps the pathways onto the planetary boundaries, presents a conceptual model (Figure 1) and a synthesis matrix (Table 1), and weighs ecological costs against the benefits that digital infrastructure provides.

2. Scope and review approach

This article is an integrative, narrative review rather than a systematic review. We searched Web of Science Core Collection, Scopus, PubMed, and Google Scholar for literature published between January 1, 2009 and April 30, 2026; final searches were completed on April 30, 2026. Searches paired the truncated phrase "data cent*" (capturing both "data center" and "data centre") and "hyperscale" with topical blocks run separately for air quality, water, noise, land, and equity, using terms such as "air pollution," "particulate matter," "nitrogen oxides," "diesel generator," "water use," "cooling," "withdrawal," "environmental flow," "noise," "low-frequency noise," "land use," "habitat fragmentation," "urban heat island," "environmental justice," and "planetary boundaries"; the full strings are reproduced in the **Appendix**. Only English-language sources were retained. Titles and abstracts were screened against three criteria: the source addresses an environmental, ecological, or health consequence of data centers, or supplies the analogous evidence used here to interpret such a consequence; it reports empirical data, a quantitative model, a legal or policy analysis, or a synthesis rather than assertion alone; and its full text is retrievable. Records passing that screen were read in full and retained where they supported a specific claim in the synthesis. Of the 48 sources cited, 31 are peer-reviewed articles, books, or book chapters and 17 are institutional reports, guidelines, or other gray literature. Gray literature was treated as authoritative only where the issuing body is a government agency, an intergovernmental organization, a university research unit, or an established research institute, and where the document states its data sources or method; news reporting and institutional press releases were used only to locate primary documents and are not cited in

support of any claim. Preprints were excluded. Where a source initially identified as a preprint had subsequently appeared as a peer-reviewed article, the published version was substituted; where it had not, the claim was either removed or attributed to an authoritative analysis that had itself adopted the estimate and is cited as the source of that attribution. Every reference was checked against the publisher record for authorship, title, year, volume, pages, and DOI, and each claim was checked against the text of the source it cites; URLs for web-based sources were verified on April 30, 2026.

Each substantive claim is assigned to one of three evidence tiers. Established denotes a directly measured or directly observed result reported in the peer-reviewed literature or in a primary regulatory or monitoring dataset, such as permitted and reported emissions compiled by a state environmental agency; a measurement reported only in commercial or advocacy material does not qualify. Modeled denotes a quantitative estimate generated by peer-reviewed or institutional modeling, including dispersion, life-cycle, and health-impact modeling, in which the quantity is inferred from parameters rather than measured at the point of interest. Inferred denotes an expectation extrapolated from analogous literature outside the data center context, with no corresponding observation at or near a data center. Because these tiers often differ within a single pathway, Table 1 assigns a tier to each individual claim rather than to a pathway as a whole, and records whether the claim concerns a pressure, the attribution of that pressure to data centers, a resulting ecological or health outcome, or the magnitude of that outcome. This is a synthesis of a dispersed literature, not a systematic review conducted according to Preferred Reporting Items for Systematic reviews and Meta-Analyses guidance, and the balance of sources reflects what is currently available rather than a claim that the evidence is mature.

3. Conceptual framework: Data centers as socio-ecological disturbances

Traditional assessments of data center sustainability often rely on separate metrics: tons of CO_2, megawatts consumed, and gallons of water withdrawn. An ecological approach treats data centers as nodes in socio-ecological systems, where decisions about energy sourcing, cooling technology, siting, and scale affect atmospheric, hydrological, terrestrial, and social systems at the same time. Building on the frameworks proposed by Tao and Gao,[1] Gour *et al.*,[2] Ngata *et al.*,[3] Lifset *et al.*,[4] and the broader sustainability science literature, this article distinguishes five interrelated impact pathways.

The framework integrates existing work rather than simply classifying harms. Tao and Gao[1] frame data center growth primarily as an emerging human health problem, and Gour *et al.*[2] provide a single-region assessment of Virginia's Data Center Alley that is largely oriented toward health. Ngata *et al.*[3] add a community-level mixed-methods account of environmental and socioeconomic strain, while Lifset *et al.*[4] locate these concerns within electric-grid governance, transmission planning, fossil-fuel lock-in, and local environmental law. This article extends those works in three ways. First, it treats atmospheric, freshwater, acoustic, terrestrial, and social effects as one coupled system and identifies feedbacks through which one pathway can intensify another. Second, it maps each pathway onto the planetary boundaries so that one infrastructure sector can be assessed against several biophysical limits at once. Third, it grades evidence explicitly, which turns the framework into a research agenda by showing where established findings end and hypotheses begin. The framework is designed for operational use: each pathway corresponds to measurable indicators, including ambient fine particulate matter with an aerodynamic diameter of 2.5 μm or less ($PM_{2.5}$) and NO_x, withdrawal as a share of basin flow, low-frequency sound levels at receptors, and impervious-area and habitat-connectivity metrics. The couplings can be represented as testable feedback relationships in linked energy, water, and land models. Figure 1 presents the model, and Table 1 summarizes the pathways in an assessment matrix that assigns an evidence tier to each individual claim and pairs it with an illustrative magnitude and the corresponding research gap. Table A1 specifies, for each pathway, the indicator, unit, spatial and temporal scale, candidate data source, expected direction of effect, evidence tier, and principal confounders required to test it.

We use several terms in specific senses. Ecological sustainability refers to maintaining the structure and function of ecosystems and the biophysical processes on which they depend, so that their capacity to support life is not eroded over time. Environmental degradation refers to measurable declines in the quality of air, water, soil, acoustic environments, or habitat. A socio-ecological system couples human decisions and ecological processes that mutually shape one another. Sustainability justice, as used here, encompasses distributive concerns (who bears costs and who gains benefits), procedural concerns (who participates in decisions), and recognition concerns (whose knowledge and harms are acknowledged).

The first pathway is atmospheric degradation. This encompasses both greenhouse gas emissions contributing to climate forcing and the release of criteria air pollutants ($PM_{2.5}$, NO_x, and SO_2) from fossil-fuel power plants and on-site diesel generators. These emissions degrade regional

air quality, contribute to acid deposition that harms forests and freshwater ecosystems, generate tropospheric ozone that damages vegetation, and impose direct burdens on human respiratory and cardiovascular health.[5,6]

The second pathway is freshwater depletion and aquatic ecosystem disruption. Evaporative cooling systems consume enormous volumes of water, often drawn from municipal supplies or local aquifers in regions already facing scarcity. Thermal and chemical discharges from cooling operations alter the temperature, salinity, and microbial ecology of receiving waterways.[11-13]

The third pathway is acoustic disturbance. Cooling systems operate continuously, backup generators undergo periodic testing, and the aggregate noise footprint of industrial campuses creates persistent acoustic environments that affect both human communities and local wildlife. Research in acoustic ecology demonstrates that anthropogenic noise reshapes animal behavior, communication, and habitat use, with consequences for biodiversity that parallel the well-documented effects on human sleep and cardiovascular health.[2]

The fourth pathway is land-use transformation and habitat fragmentation. Large hyperscale data centers convert agricultural land, forests, and open spaces into impervious industrial surfaces, fragmenting habitats, disrupting wildlife corridors, and intensifying urban heat island effects. Associated transmission infrastructure (substations, power lines, and access roads) extends the disturbance footprint well beyond the facility boundaries.[14]

The fifth pathway encompasses sustainability justice and distributional inequity. The ecological and social costs of data centers are distributed unevenly, with communities that are already ecologically stressed and socially disadvantaged bearing disproportionate burdens from polluted air, depleted water, industrial noise, and landscape transformation, even as the economic benefits of digital services accrue elsewhere.[2,5,14]

These pathways are mediated by siting decisions, regulatory regimes, technological choices (cooling system design, backup power technology, and energy sourcing), and broader patterns of structural inequality. They also interact, and Figure 1 labels four principal cross-pathway feedbacks, each of which is formulated as a testable proposition.

(i) F1: shifting from evaporative to air cooling in water-stressed basins lowers consumptive water use but raises electricity demand, so that a measured reduction in site water intensity should be accompanied by a measurable rise in grid-attributable emissions per unit of computation.

(ii) F2: canopy removal, impervious cover, and waste-heat rejection raise local air and surface temperatures, thereby increasing cooling loads and, in turn, emissions and water use, so that heat-island intensity around a campus should predict its cooling energy at a given ambient temperature.

(iii) F3: continuous low-frequency noise and structural fragmentation act on the same receptors, so that their combined effect on effective habitat should exceed the effect of either alone.

(iv) F4: the burdens generated by the first three feedbacks fall on places selected partly for low land cost and limited regulatory capacity, so that the distribution of exposure should track prior environmental burden and weak procedural protection rather than the distribution of computational benefit.

The electricity pathway also has a commons structure: as Thomson[15] argues in the cryptocurrency-mining context, energy-intensive computing can shift local energy, health, and environmental costs onto regions that supply cheap or underregulated power while the economic gains flow elsewhere. The following sections review the evidence in each domain, highlighting established facts and areas of uncertainty.

3.1. Mapping impacts onto planetary boundaries

Reading the five pathways against the planetary boundaries framework[9,10] shows why data center impacts should not be assessed one pollutant at a time. Atmospheric degradation loads the climate-change boundary through CO_2 and the biogeochemical-flow boundary through nitrogen and sulfur emissions and downstream nutrient deposition. Freshwater depletion bears directly on the freshwater-change boundary, which the 2023 update identifies as already transgressed, through consumptive blue-water use and altered flows. Land-use transformation contributes to land-system change through the conversion of vegetated land to impervious surfaces. Acoustic disturbance and habitat fragmentation both erode biosphere integrity, the boundary governing the functional and genetic diversity of living systems. The relative magnitude of these contributions is uncertain and differs by boundary. The climate and biogeochemical contributions are the best quantified, although still largely modeled; the freshwater contribution is large in absolute terms but concentrated in particular basins, so its significance is regional rather than global; and the biosphere-integrity contribution is currently the least quantified, resting mainly on inference from analogous literature. This mapping does not measure the aggregate footprint, but it indicates that the footprint spans at least four boundaries and cannot be judged sustainable through single-pathway accounting.

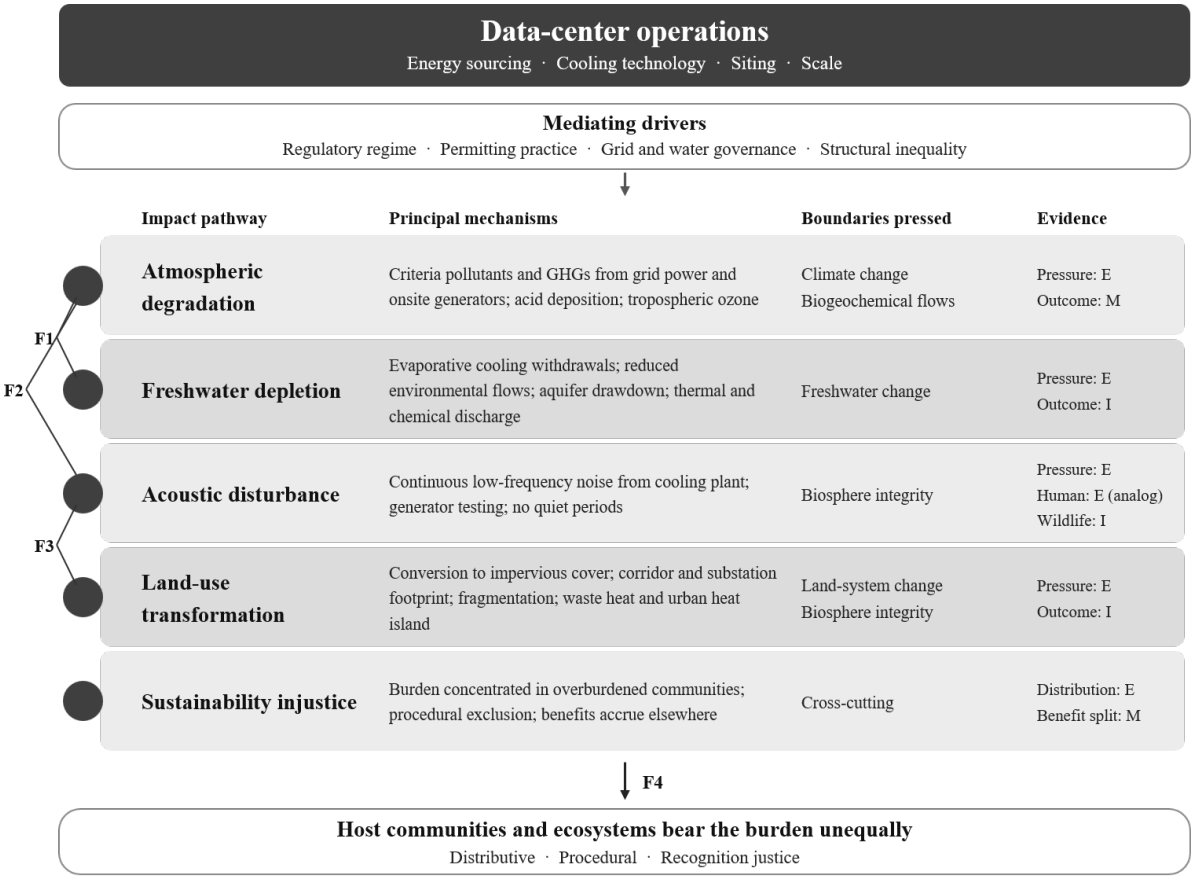


Figure 1. Data centers as socio-ecological disturbances. Conceptual model showing five interacting impact pathways through which data-center operations may affect socio-ecological systems: atmospheric degradation, freshwater depletion, acoustic disturbance, land-use transformation, and sustainability justice and distributional inequity. Operational decisions (energy sourcing, cooling technology, siting, and scale), shaped by regulation and structural inequality, drive five interacting impact pathways that place pressure on multiple planetary boundaries and distribute burdens unequally across host communities and ecosystems. Feedbacks are indicated by F1–F4: F1, shifts in cooling technology can trade water use against electricity consumption and associated emissions; F2, canopy loss and waste heat can increase cooling loads; F3, noise and habitat fragmentation can act jointly on the same habitat; and F4, burdens may become concentrated where regulatory capacity is weakest. Evidence tiers indicate the level of support for each claim: E: Established; M: Modeled; I: Inferred.

4. Atmospheric degradation: Climate forcing, air quality, and ecosystem damage

4.1. Emissions sources and magnitude

Data centers contribute to atmospheric degradation through three emission scopes. Scope 1 emissions originate from on-site diesel backup generators and, in some facilities, gas turbines used as supplementary power sources, which emit NO_x, primary particulate matter, and volatile organic compounds during testing and operation.[5,6] Research at Virginia Commonwealth University mapped permitted and reported emissions from 138 data centers across Northern Virginia and found that generator emissions rose sharply between 2015 and 2023, with reported carbon monoxide up by 196%, NO_x by 111%, and particulate matter by 139%. In neighborhoods close to clusters of facilities, cumulative emissions exposure is already comparable to, and in places exceeds, exposure from the region's notable point sources, including the Possum Point power station, and would rise substantially further if facilities emitted at their permitted ceilings.[16] Scope 2 emissions arise from fossil-fuel electricity generation serving grid-connected data centers, including $PM_{2.5}$, NO_x, and SO_2. Dandres *et al.*[17], using consequential prospective life-cycle assessment for future Canadian data center deployment, show why grid context matters: the environmental consequences of new facilities depend on marginal electricity sources, electricity trade, and broader power-system response rather than facility efficiency alone. Scope 3 emissions, including those from semiconductor manufacturing and equipment supply chains, add further atmospheric burden.

Diesel exhaust presents a particular ecological and health hazard. The International Agency for Research on Cancer classified diesel engine exhaust as Group 1 (carcinogenic to humans) in 2012,[18] with sufficient evidence of elevated lung cancer risk. Communities located downwind of generator testing at data centers experience episodic but potentially high-concentration diesel exhaust plumes that degrade local air quality and deposit pollutants on surrounding vegetation and soil.

4.2. Ecological consequences beyond human health

Most existing analyses quantify data center air pollution in terms of human morbidity and mortality, but the ecological consequences extend further. NO_x and SO_2 emissions are precursors to acid deposition, which acidifies soils, leaches essential base cations from forest ecosystems, mobilizes aluminum toxic to plant roots, and acidifies freshwater bodies with well-documented consequences for fish populations, amphibians, and macroinvertebrate communities. Even though acid rain has declined substantially in North America since the 1990 Clean Air Act Amendments, more NO_x and SO_2 emissions from the growing data center industry could undo those improvements, particularly in sensitive areas like the Appalachian forests and Adirondack watersheds that are downwind of major data centers and power plants.

Tropospheric ozone is created when NO_x reacts with volatile organic compounds in sunlight, and it harms plant tissues, lowers photosynthesis, and reduces crop yields and forest productivity. Data center regions that already struggle with ozone nonattainment, including parts of Northern Virginia, the Dallas-Fort Worth corridor, and portions of the San Francisco Bay Area, face additional ozone precursor loads as data center electricity demand grows. Fine particulate matter settling on leaves makes photosynthesis less effective and can change how nutrients cycle in plants, while settling on water surfaces adds nutrients to delicate water bodies.

4.3. Modeled pollution burdens

Institutional and policy analyses provide the most developed estimates of data-center-related air pollution burdens currently available outside the preprint literature. The Federation of American Scientists[5] estimates that air pollution attributable to U.S. data centers caused roughly US$5 billion in health damages in 2023 and projects an annual burden of up to US$20 billion by 2030 under continued growth with current energy sources, while the Environmental Health Project[6] summarizes projections of substantial asthma symptom cases and premature deaths under continued growth scenarios. These estimates remain modeled rather than directly measured in exposed communities, but they are consistent with the broader epidemiological evidence linking $PM_{2.5}$, NO_x, and SO_2 to respiratory and cardiovascular disease.

Regional analyses reinforce these projections. An assessment of California data centers prepared by researchers at the University of California, Riverside, estimated that modeled health impacts from data center pollution tripled between 2019 and 2023 and could rise by a further 72% by 2028, reaching roughly 3,900 asthma cases and US$266 million in annual health costs statewide.[19] Dominici and Vartziotis[20] argue for building environmental health analysis into decisions about artificial intelligence (AI) infrastructure and illustrate the case with a health impact assessment of a proposed gas plant serving a data center campus. That assessment, prepared by the Harvard Data Science Initiative and the Dominici Lab for a proposed 3,500 MW plant serving twelve hyperscale data centers in Pittsylvania County, Virginia, estimated at least 326 tons of $PM_{2.5}$ emissions per year, exposure of more than 17,500 county residents to concentrations associated with severe health effects, and roughly US$31 million in additional annual health costs rising to more than US$625 million cumulatively by 2040. It was released days before the county board of supervisors denied the rezoning application in April 2025.[21]

A closely related peer-reviewed model analysis is Guidi *et al*.,[22] who examined pollution from 34 major Bitcoin mining operations consuming 32.3 terawatt-hours annually. Published in *Nature Communications*, the study estimated that 1.9 million Americans were exposed to at least 0.1 μg/m^3 of additional $PM_{2.5}$, with pollution crossing state lines. Those exposures were derived by attributing marginal generation to the mines and modeling dispersion, not by ambient measurement in the affected communities, and the estimate is therefore modeled rather than observed. Thomson's[15] legal analysis of cryptocurrency mining anticipates the same regulatory problem now visible in AI-oriented data centers: mobile, energy-intensive digital facilities can capture local energy advantages while leaving host regions with air pollution, rate pressure, and stranded infrastructure risks. Henneman *et al*.,[23] using 650 million person-years of Medicare data published in *Science*, found that coal-derived $PM_{2.5}$ is associated with 2.1 times greater mortality risk than $PM_{2.5}$ from all sources combined. The IEA[7] projects that fossil fuels will meet more than 40% of additional electricity demand through 2030 unless deliberate policy interventions accelerate decarbonization.

5. Freshwater depletion and aquatic ecosystem disruption

5.1. Scale and concentration of water consumption

Large data centers are among the most water-intensive industrial facilities in operation today. The Environmental and Energy Study Institute estimates that a medium-sized data center can consume approximately 110 million gallons of water per year, equivalent to the annual use of about 1,000 households, while larger facilities can use up to 5 million gallons per day, roughly equivalent to a town of 10,000 to 50,000 residents.[11] Across more than 5,000 U.S. data centers, combined direct water consumption is estimated at well over 100 billion gallons annually, with indirect water use through electricity generation adding hundreds of billions more.[11] The Brookings Institution reports that a typical data center draws about 300,000 gallons per day for cooling, comparable to the demand of roughly 1,000 households, while the largest AI-oriented facilities can consume up to 5 million gallons daily, often from municipal drinking water systems already under strain.[12]

The geographic concentration of this demand amplifies its ecological significance. In The Dalles, Oregon, Google's withdrawals reportedly accounted for more than a quarter of the city's water supply in 2023.[24] Annual water-related capital and operating expenditures for U.S. data centers are projected to grow by more than 30% between 2025 and 2030.[24] Chung *et al.*[25] reported that a large share of new AI-oriented data center capacity is being sited in regions already facing medium-to-high water scarcity risk, a pattern that concentrates consumptive demand in basins where freshwater ecosystems are already under stress.

5.2. Consequences for freshwater ecosystems

The ecological implications of water use in data centers extend well beyond human water security, although the mechanisms set out in this section are anticipated rather than observed: no published study has measured ecological change in a receiving water body attributable to data center withdrawals. Where facilities draw heavily from surface water or from aquifers hydraulically connected to streams and rivers, they reduce environmental flows, the volumes of water that remain in waterways to sustain aquatic ecosystems. The ecological consequences of flow alteration are themselves well established. A review of 165 studies of altered flow regimes found consistent declines in the abundance and diversity of fish, macroinvertebrates, and riparian vegetation across all forms of alteration, with the risk of ecological change rising as the degree of alteration increases.[26] Reduced base flows during dry seasons concentrate pollutants, elevate water temperatures, and shrink the wetted habitat available to fish, macroinvertebrates, and riparian species. In arid and semi-arid regions where many new data centers are being sited, modest reductions in environmental flow may push streams past ecological thresholds, converting perennial reaches to intermittent ones and removing habitat for flow-dependent species. That expectation follows from the flow-ecology literature rather than from any measurement at a data center.

Sustained pumping lowers water tables and reduces discharge to springs and to groundwater-dependent wetlands that support distinctive ecological communities. The mechanism by which well withdrawals propagate into streamflow depletion is well characterized in hydrological science, including the lag that can separate the onset of pumping from measurable depletion and that allows effects to accumulate before they are detected.[27] Where water tables fall below the discharge or rooting thresholds on which groundwater-dependent ecosystems rely, recovery can be slow and in some settings effectively irreversible. Whether data center pumping is producing such effects is unknown, since no study has measured drawdown or ecosystem response attributable to a data center. The concentration of demand in water-stressed basins is nonetheless reason enough to treat these questions as a priority for freshwater biodiversity conservation.

Facilities using once-through cooling or discharging cooling tower blowdown return water to the environment with elevated salinity, turbidity, heavy metals, and microbial contaminants.[13] High salinity disrupts freshwater organisms adapted to low-conductivity environments, can corrode infrastructure, and increases municipal wastewater treatment costs. Thermal discharge from once-through cooling warms receiving waterways, promoting cyanobacterial bloom formation and Vibrio proliferation, both carrying well-documented consequences including gastroenteritis, septicemia, and cyanotoxin exposure in humans, as well as ecological harm through oxygen depletion, algal dominance, and loss of thermal refugia for cold-water species.

5.3. Human dimensions of water stress

The water demand from data centers also affects human systems. When withdrawals stress municipal supplies, they can worsen scarcity and reliability problems, especially in drought-prone regions, increasing the risk of supply interruptions that compromise hygiene, food safety, and healthcare operations. Competition between industrial and residential users can raise water tariffs, disproportionately burdening lower-income households with downstream

effects on nutrition, sanitation, and mental health.[2] Ngata *et al.*[3] place these concerns in a community-level frame, treating water use, infrastructure strain, economic burden, and health impacts as connected effects of siting data centers near existing communities. Shifts to less water-intensive cooling technologies, adopted in response to scarcity, can increase electricity demand and thus air pollution burdens, illustrating the pathway interactions that make siloed analysis inadequate. Direct empirical studies linking water use in data centers to specific ecological or health outcomes are not yet available, but the combination of high, localized consumption and siting in water-stressed regions supports including water-related risks in sustainability impact assessments of proposed and existing facilities.[12,14]

6. Acoustic disturbance: Ecological and community dimensions

6.1. Noise characteristics of data centers

Data center campuses generate persistent industrial noise from cooling systems (e.g., chillers, cooling towers, air-handling units, and condenser fans) and periodic testing of diesel backup generators, sometimes at night or early morning. Internal noise levels of 70 to 90 dBA and community-facing levels exceeding 48 to 60 dBA without adequate mitigation have been reported.[2,14] Cooling systems produce noise dominated by low-frequency components below 250 Hz, a spectral character that standard A-weighted measurements systematically underestimate. Thakre and Vijay[28] found a 39.4 dB discrepancy between A-weighted and C-weighted measurements inside adjacent residences, showing that regulatory monitoring based on A-weighting alone can miss much of the low-frequency burden. Baliatsas *et al.*[29] report a pooled prevalence of roughly 11% for high annoyance attributed to low-frequency noise in general population samples, while cautioning that the observational evidence base is small and methodologically heterogeneous. Since the low-frequency component is poorly captured by A-weighting, exposure of this kind is systematically understated by the metric on which most regulatory monitoring relies.

6.2. Impacts on human communities

In the absence of data center-specific epidemiology, inference must draw on the extensive environmental noise and health literature. Systematic reviews for the World Health Organization's (WHO) Environmental Noise Guidelines provide strong evidence that long-term noise exposure increases risks of ischemic heart disease, hypertension, and other cardiometabolic outcomes.[30,31] A meta-analysis underpinning the guidelines found that each 10 dB increase in day-evening-night noise from road traffic was associated with an 8% increase in ischemic heart disease incidence.[30] The WHO estimates approximately 48,000 new cases of ischemic heart disease and 12,000 premature deaths annually attributable to environmental noise across Europe, with at least 1.6 million healthy life-years lost annually due to traffic noise in Western Europe alone.[31-33]

The biological mechanisms are well characterized: noise activates neuroendocrine pathways, elevates stress hormones and blood pressure, and disrupts sleep, which in turn elevates cardiovascular risk.[30,34] WHO guidelines recommend maximum nighttime outdoor levels of 40 dB to avoid adverse effects.[35] A meta-analysis by Liang *et al.*,[36] published in *BMC Public Health*, found that low-frequency noise exposure significantly impairs higher-order cognitive functions, a finding potentially relevant to communities near around-the-clock data centers, which are increasingly being developed in suburban and exurban residential areas.

6.3. Acoustic ecology: Wildlife and ecosystem effects

The ecological dimension of noise pollution from data centers has received little attention in the data center literature, and no study has measured wildlife responses at or near such a facility. The concern rests instead on evidence from acoustic ecology. Chronic anthropogenic noise is recognized there as a widespread form of environmental degradation that alters behavior, masks acoustic signals, redistributes species across landscapes, and lowers reproductive success.[37] A synthesis of two decades of research across taxa documents behavioral and physiological responses at sound levels routinely produced by industrial and transport sources, with birds, amphibians, and bats among the better studied groups.[38] Birds in noisy environments shift song frequencies, hold smaller territories, and fledge fewer young; amphibians, which depend on acoustic signaling for mate choice, are vulnerable to low-frequency noise that overlaps their call bands; and nocturnal foragers, including bats, can be displaced from foraging habitat by persistent nighttime noise. Whether the continuous output of cooling plants produces these effects around data center campuses has not been tested.

The continuous, low-frequency acoustic signature of data center campuses is ecologically distinctive. Unlike transportation noise, which fluctuates with traffic patterns, data center noise is effectively constant, leaving no predictable quiet periods. In other settings, sustained noise of this character is associated with chronic physiological stress in exposed animal populations, and a comparable

response would be anticipated here. Where multiple hyperscale campuses are clustered, as in Northern Virginia or central Oregon, the cumulative footprint may create acoustic exclusion zones from which noise-sensitive species are displaced. This expectation is drawn from acoustic ecology rather than from studies at data centers, and it remains untested; were it supported by future work, it would represent a form of local biodiversity loss rarely attributed to digital infrastructure.

7. Land-use transformation, habitat fragmentation, and urban ecology

Hyperscale data center campuses occupy enormous land areas, often tens or hundreds of acres per facility, and their associated infrastructure (substations, transmission lines, access roads, water and sewer connections) extends the disturbance footprint considerably further.[14] Lifset *et al.*[4] emphasize that local impacts include transmission corridors, power-plant decisions, distribution infrastructure, and ratepayer costs, which means land-use impacts should be measured beyond the property boundary of the data center itself. These facilities are frequently sited on agricultural land, forest margins, or semi-rural open space at the exurban fringe, precisely the landscape matrix that provides habitat connectivity, supports pollinator populations, and delivers ecosystem services such as stormwater infiltration, carbon sequestration, and local climate moderation.

The conversion of permeable land cover to impervious surfaces (rooftops, parking areas, and access roads) increases stormwater runoff volume and velocity, carrying thermal loads, sediments, and pollutants into adjacent waterways. This hydrological disruption compounds the direct water withdrawal impacts discussed in **Section 5**. Removal of tree cover eliminates canopy interception, reduces evapotranspiration, and removes both carbon sinks and local cooling capacity, creating positive feedback loops in which the campus itself generates additional heat that must then be dissipated through yet more energy-intensive and water-intensive cooling.

Habitat fragmentation may be the most ecologically consequential and least studied aspect of converting land for data centers. Long-running experimental and observational work across biomes shows that fragmentation reduces biodiversity, weakens ecosystem functions such as nutrient retention and pollination, and produces effects that continue to accumulate for decades after habitat is first divided.[39] Applied to data center campuses, this implies that where large sites and their associated infrastructure interrupt wildlife corridors, they should reduce the effective habitat available to wide-ranging species, increase edge effects, and isolate populations in ways that lower genetic diversity and raise extinction risk. Cumulative fragmentation from clusters of facilities, a pattern emerging in Northern Virginia, central Texas, and the greater Phoenix area, could convert a functioning ecological landscape into a patchwork of remnants too small to sustain viable populations of area-sensitive species. As with the acoustic effects above, these consequences are inferred from landscape ecology rather than documented at data centers, and they warrant direct study.

Urban heat island intensification is another ecological and sustainability concern. Data centers produce large volumes of waste heat. Almost all of the electricity they draw is converted to heat that must be released into the environment. When concentrated in dense campus configurations, this thermal output elevates ambient temperatures in surrounding areas, increasing cooling demand for both the data centers themselves and neighboring residential and commercial buildings, and stressing urban vegetation and wildlife adapted to pre-development thermal regimes. Gour *et al.*[2] note that data centers affect community well-being through dimensions beyond strictly biomedical outcomes, including perceived loss of rural or suburban character, landscape transformation, and anxiety about infrastructure reliability and future environmental change.

8. Sustainability justice: The unequal distribution of ecological burdens

A consistent finding across the emerging data center literature is that ecological and social burdens are distributed unevenly. Institutional and policy analyses identify communities near fossil-fuel power plants, backup generators, and new transmission infrastructure as especially exposed to data-center-related air pollution and infrastructure burdens.[4-6,14] Ngata *et al.*[3] document these issues at the community scale in Northern Virginia, where residents described data center growth through linked concerns about water use, noise, power quality, air pollution, economic burden, and the power dynamics that shape who benefits and who bears the costs. Many heavily impacted host communities also face existing environmental burdens and limited capacity to participate in technical permitting processes.

Case-study work in Virginia's Data Center Alley documents how large campuses have been concentrated in suburban and exurban communities with existing environmental burdens and infrastructural constraints.[2,3] Community organizations and environmental justice advocates in Northern Virginia and other hubs have

Table 1. Synthesis matrix of data center impact pathways

Pathway	Specific claim	Claim type	Tier	Illustrative magnitude and source	Priority research gap
Atmospheric degradation	Data centers emit criteria pollutants directly, from diesel and gas backup generators	Pressure	E	Permitted and reported emissions at 138 Northern Virginia facilities; reported CO +196%, NO_x +111%, PM +139% (2015–2023)[16]	Fenceline ambient monitoring; speciated diesel exhaust measurement
	Electricity generation serving data centers adds $PM_{2.5}$, NO_x, and SO_2 to regional airsheds	Attribution	M	Marginal-generation and dispersion modeling; 1.9 million people exposed to ≥0.1 μg/m^3 from 34 bitcoin mines[22]	Attribution of measured ambient concentrations to identified facilities
	The associated public health burden is large and rising	Magnitude	M	US: ~US$5 billion (2023) rising to as much as US$20 billion per year by 2030[5]; California: ~3,900 asthma cases and US$266 million per year by 2028[19]	Cohort and quasi-experimental designs; data-center-specific DALYs
	Acid deposition and tropospheric ozone from these emissions damage forests, soils and surface waters	Outcome	I	Established for the pollutants in general; no deposition or ozone effect has been attributed to data center loads	Deposition and ozone monitoring in data center corridors
Freshwater depletion	Facilities consume large volumes of water for evaporative cooling	Pressure	E	Medium facility ~110 million gallons/year; largest AI sites up to 5 million gallons/day; The Dalles, OR >25% of city supply (2023)[11,12,24]	Standardized facility-level disclosure of withdrawal and consumption
	New capacity is concentrated in water-scarce basins	Attribution	M	Market analysis of announced capacity against basin water-stress indices[25]	Independent basin-scale accounting of cumulative demand
	Withdrawals reduce environmental flows and deplete streamflow through connected aquifers	Outcome	I	Mechanism established in flow-ecology and groundwater science;[26,27] not measured at any data center	Paired hydrological and biological monitoring at operating facilities
	Discharge alters salinity, temperature and microbial ecology of receiving waters	Outcome	I	Discharge chemistry characterized in the water-utility literature;[13] ecological response not measured	Receiving-water monitoring before and after commissioning
Acoustic disturbance	Campuses generate continuous noise dominated by components below 250 Hz	Pressure	E	Internal 70–90 dBA; community-facing levels above 48–60 dBA without mitigation[2,14]	Public, standardized long-term monitoring at sensitive receptors
	A-weighted monitoring understates the low-frequency component of that exposure	Pressure	E	39.4 dB difference between A- and C-weighted levels inside adjacent residences[28]	Adoption of C-weighted or narrow-band criteria in permitting
	Long-term environmental noise exposure raises cardiometabolic risk (general evidence)	Outcome	E	+8% ischemic heart disease per 10 dB Ld_{en}; ~48,000 cases and ~12,000 premature deaths per year in Europe[30,31-33]	Exposure-response functions for continuous industrial low-frequency sources
	Residents near data centers experience these effects	Attribution	I	No epidemiological study has used data center proximity as an exposure	Longitudinal community exposure and health studies at campuses
	Wildlife are displaced or physiologically stressed by campus noise	Outcome	I	Established for chronic anthropogenic noise generally;[37,38] untested at data centers	Acoustic-displacement fieldwork at clustered campuses
Land-use change and fragmentation	Campuses and their off-site infrastructure convert vegetated land to impervious surfaces	Pressure	E	Tens to hundreds of acres per campus, plus substations, transmission corridors and roads[14]	Consistent accounting of the off-site disturbance footprint
	Conversion fragments habitat and reduces landscape connectivity	Outcome	I	Fragmentation effects established across biomes;[39] not measured at data centers	Connectivity and biodiversity studies at campus clusters
	Waste heat and impervious cover intensify local heat islands, raising cooling demand	Outcome	I	Nearly all drawn electricity is released as heat; heat-island mechanism established for industrial land cover generally	Thermal mapping and stormwater quantification around campuses

(*Cont' d...*)

Table 1. (***Continued***)

Pathway	Specific claim	Claim type	Tier	Illustrative magnitude and source	Priority research gap
Sustainability justice	Burdens concentrate in communities with prior environmental burden and limited procedural capacity	Attribution	E	Case and policy analyses in Northern Virginia and other hubs[2-6,14,16]	Quantitative cumulative-burden mapping across host regions
	Benefits accrue largely outside host communities	Outcome	M	Contested local fiscal and employment claims set against documented infrastructure and ratepayer costs[3,4]	Independent evaluation of local benefit capture over time
	Procedural and recognition failures shape siting outcomes	Attribution	E	Documented late notice, limited technical disclosure and rapid permitting[6,14]	Evaluation of community benefit agreements and participatory siting

Notes: Each row presents a single claim, its claim type and evidence tier, an illustrative magnitude and source, and the corresponding priority research gap. Evidence tiers are defined as follows: E, established; M, modeled; and I, inferred (see **Section 2**). Claim types are defined as follows: pressure, evidence that the physical loading exists; attribution, evidence that the loading is traceable to data centers; outcome, evidence that an ecological or health consequence follows; and magnitude, evidence concerning the size of that consequence.
Abbreviations: AI: Artificial intelligence; CO: Carbon monoxide; DALY: Disability-adjusted life year; NO_x: Nitrogen oxides; PM: Particulate matter; $PM_{2.5}$: Fine particulate matter with an aerodynamic diameter of 2.5 μm or less; SO_2: Sulfur dioxide.

raised concerns about cumulative impacts from air and noise pollution, the siting of new transmission infrastructure, and potential impacts on private wells and small water systems.[14,16] The Federation of American Scientists[5] highlights that data center pollution costs fall disproportionately on communities near fossil-fuel power plants and backup generators, many of which are low-income communities or communities of color.

The distributional pattern in water mirrors that of air quality. Chung *et al.*[25] reported that a large share of new AI-oriented data center capacity is being built in regions facing medium-to-high water scarcity risk, raising questions about who bears the costs of reduced water availability. The Lincoln Institute of Land Policy[14] documents cases in which municipal water infrastructure was strained by a sudden increase in demand from data centers without adequate advance planning or community input.

Distribution is only one dimension of the problem. A fuller account of sustainability justice also asks who decides and whose concerns are recognized. In many host regions, permitting has moved quickly, technical information about emissions, water use, and noise has been limited or proprietary, and residents have learned of large projects late in the process.[6,14] These are procedural failures as much as distributive ones. Strengthening procedural and recognition justice would mean engaging communities early and in accessible terms, publishing the operational data needed to evaluate impacts, providing technical and legal support so that under-resourced communities can participate on comparable footing, and giving residents genuine influence over whether and how facilities are sited, including the standing to say no. Community benefit agreements, independent monitoring, and formal roles for affected residents in siting and permitting can help align the people who bear the burdens with the people who shape the decisions.[2] Recognition also means treating non-biomedical harms, such as loss of rural character, sleep disruption, and anxiety about future change, as legitimate considerations rather than as externalities.

From a sustainability justice perspective, this distributional pattern is especially concerning because the communities bearing the greatest ecological and health burdens are usually not the primary beneficiaries of the computing services these facilities provide. The economic geography of digital infrastructure creates a spatial mismatch: computational benefits flow to urban knowledge workers and global technology firms, while environmental costs are externalized to rural, exurban, and disadvantaged communities whose political capacity to resist industrial siting is often limited. Mullany[40] makes this rural-health framing explicit, describing AI data centers as resource-extractive infrastructure whose public-health consequences are often absent from university discussions of AI ethics. The pattern echoes a longstanding finding in environmental justice scholarship, where communities that host concentrated industrial burden while the benefits accrue elsewhere have been described as sacrifice zones. The term is used here in Lerner's[41] sense: fenceline communities that carry disproportionate chemical exposure and have limited political capacity to refuse it. A fairer distribution of the benefits and costs of digital infrastructure is a condition of sustainable development as defined by the Brundtland Commission and operationalized through the United Nations Sustainable Development Goals.

9. Occupational health and broader community well-being

In addition to community-level exposures, data center workers face occupational risks related to noise, indoor air quality, ergonomic strain, and psychosocial factors. Peer-reviewed literature specifically examining occupational health outcomes in data center workers is extremely limited, with existing guidance deriving from general occupational safety standards for noise, chemical exposures (including diesel exhaust during generator maintenance), and indoor environmental quality. Given the documented community-level evidence of low-frequency noise and diesel exhaust hazards, a targeted occupational cohort study at large data center campuses would contribute meaningfully to both occupational and environmental health science.

Surveys and qualitative studies in heavily impacted regions report community concerns about sleep disturbance, property values, distrust in permitting processes, water use, air pollution, infrastructure reliability, and economic burden.[3,6,14] Mullany[40] also argues that rural communities hosting AI data centers should be treated as public-health communities, not merely as sites for land assembly and energy procurement. The mental health consequences of involuntary, persistent noise exposure are an underexplored domain; existing research documents elevated rates of psychological distress, anxiety, and depression in chronically noise-exposed populations. As data centers expand into residential corridors, longitudinal research on mental health outcomes in affected communities would fill a significant gap.

10. Benefits, trade-offs, and the net sustainability balance

A defensible sustainability assessment weighs benefits as well as costs, and data center infrastructure provides substantial benefits. Data centers provide support for services on which modern economic, scientific, medical, and civic life depends on, including cloud computing, communications, health records, remote education, financial systems, and large-scale scientific computing. They generate economic activity, construction and operational employment, and tax revenue that can fund local services, although the durability and local capture of those benefits vary widely and remain contested in many host communities. Ngata *et al.*[3] and Lifset *et al.*[4] make that contestation visible at the local scale, where promised tax revenue and jobs must be weighed against water demand, noise, energy infrastructure, ratepayer costs, and community control. Any judgment about whether a given facility or a given rate of growth is sustainable must set these gains against the ecological and social costs described above.

Digital infrastructure can also enable environmental benefits, and these deserve explicit accounting. AI and advanced computing are being used to optimize electricity grids, industrial processes, buildings, and logistics; to accelerate discovery of materials, including catalysts and battery and carbon-capture chemistries; to improve climate and weather modeling; and to support precision agriculture and conservation monitoring. Digital substitution can displace more resource-intensive activities, as when videoconferencing replaces air travel or digital media replaces physical production and distribution. Sinistore *et al.*[42] argue that AI holds real potential to reduce emissions in other sectors, but only if the burdens of enabling it, including manufacturing, energy, water, and land, do not outpace those gains.

The evidence for these benefits is uneven. Efficiency and optimization gains from specific applications are often established at the level of the individual system, whereas economy-wide environmental benefits are usually modeled and depend on assumptions about how the technology is deployed. They are also subject to rebound effects: efficiency improvements can lower the effective cost of computation and stimulate additional demand, so that absolute energy, water, and land use continue to rise even as impact per computation falls.[7] The sustainability question is whether the net effect of digital infrastructure, including its distribution, stays within ecological limits. On present evidence, supply-side efficiency alone is unlikely to offset projected demand growth, which is why the policy discussion below pairs efficiency with siting, stewardship, and demand-side measures.

11. Research gaps and methodological priorities

Despite the rapid expansion of data center infrastructure, direct empirical research on ecological and health impacts remains sparse, with most work focused on energy and climate rather than local exposures and outcomes.[1] A major obstacle is the lack of operational data transparency: most data center operators do not publicly disclose granular information on energy sources, water consumption, emissions, or cooling configurations, which limits independent verification of sustainability claims and impedes evidence-based policy.[8] Gour *et al.*[2] characterize their assessment as exploratory and call for transdisciplinary research integrating physical sciences, engineering, ecology, and public health. Ngata *et al.*[3] show that mixed-methods community research can reveal burdens that aggregate energy and carbon metrics miss, including lived experience, infrastructure strain, and procedural exclusion. Several gaps stand out.

First, no published epidemiologic cohort studies have followed communities near data centers as an exposure group. The closest analog is Guidi *et al*.,[22] who traced $PM_{2.5}$ from Bitcoin mining operations to affected communities, but their study examined a specialized subset of computing infrastructure. Quasi-experimental designs exploiting variation in data center construction as natural experiments could provide causal estimates while longer cohort studies mature.

Second, high-resolution measurements of ambient $PM_{2.5}$, nitrogen dioxide, ultrafine particles, and other pollutants near data centers are largely absent; the most influential analyses use modeled rather than measured concentrations. Systematic environmental noise monitoring around data center clusters, including diurnal patterns and low-frequency characterization, is similarly needed.

Third, no disability-adjusted life year (DALY) estimates specific to data centers have been published. Global $PM_{2.5}$ exposure contributed to 7.83 million deaths and 231.51 million DALYs in 2021.[43] However, no analysis has apportioned a fraction of that burden specifically to data center electricity generation. A DALY-based framework would facilitate direct comparison with other industrial sectors and inform resource allocation decisions.

Fourth, the freshwater ecological consequences of water withdrawals from data centers are essentially unstudied. No published research has examined how sustained withdrawals affect environmental flows, aquatic biodiversity, or groundwater-dependent ecosystems in data center regions. Similarly, no analysis has linked the water demand of data centers to differential rates of water supply interruptions or water quality degradation in host communities.

Fifth, the acoustic ecology impacts of data center noise on wildlife have never been studied. Given the well-established effects of anthropogenic noise on bird, amphibian, and bat populations, this represents a conspicuous gap in understanding the full ecological footprint of digital infrastructure.

Sixth, data center workers have never been studied as a distinct occupational cohort for noise-induced hearing loss, diesel exhaust exposure, or heat stress. Seventh, no comprehensive life-cycle sustainability assessment spanning data centers, 5G infrastructure, lithium mining, and electronic waste has been published to place data center impacts in the broader context of digital infrastructure's ecological footprint. Dandres *et al*.[17] show how prospective life-cycle assessment can connect data center deployment to marginal electricity generation and cross-border environmental impacts, but comparable work is needed for current AI-oriented buildout, water demand, land conversion, server manufacturing, and end-of-life electronics.

Eighth, carbon dioxide capture and adsorption at or near power sources for data centers remains an underexplored mitigation pathway. Research and policy attention has centered on efficiency, siting, and cleaner electricity, while comparatively little work has examined capturing CO_2 from the gas generation that increasingly serves these loads, or coupling data centers to emerging capture technologies. Advances in sorbent materials, including charged activated carbons and porous covalent-organic and metal-organic frameworks, and in adsorption-based separation more broadly, have improved capacity, kinetics, and regeneration energy in ways potentially relevant to point-source and direct-air capture.[44-46] Data centers present specific and largely unstudied opportunities, such as using low-grade waste heat to regenerate sorbents, that warrant techno-economic, life-cycle, and ecological assessment before capture is treated as a credible part of the sector's decarbonization.

Methodologically, the strongest path forward[5,20] involves pairing geospatial dispersion modeling and health-impact assessment tools with observational ecological and health data, and exploiting natural experiments arising from policy or technological changes.

12. Policy and planning priorities for sustainable digital infrastructure

Despite remaining uncertainties, the current evidence base supports precautionary policy action across several domains.

12.1. Energy decarbonization and emissions reduction

Prioritizing low-carbon, low-pollution electricity generation for data center loads and locating new facilities in regions with cleaner grids can reduce both climate forcing and local ecological damage per unit of computation.[7,8] Dandres *et al*.[17] show that siting decisions should account for marginal electricity generation and power-system response, since apparent local grid cleanliness can shift environmental burdens to connected regions through reduced exports or new fossil generation. Emerging research demonstrates that intelligent operational controls can yield meaningful gains: Xiao and You,[47] using deep reinforcement learning across ten globally representative sites, achieved over 6% energy reduction and over 8% water savings relative to standard baseline controllers, with carbon abatement costs ranging from US$107

to US$500 per metric ton when paired with on-site renewable adoption. Restrictions on diesel generator use, including tighter limits on hours of operation, mandates for best available control technologies, and transitions to battery storage, renewable-based microgrids, or lower-emission alternatives, can mitigate local air pollution and its cascading ecological effects.[5,6] Where gas generation is unavoidable in the near term, point-source carbon capture may become a complementary option, though it remains costly and unproven at this scale and should not displace decarbonization of supply (see **Section 11**).

12.2. Water stewardship and aquatic ecosystem protection

Incorporating data center demand explicitly into watershed-level water resource planning, especially in water-stressed basins, and prioritizing reclaimed water or closed-loop cooling can reduce stress on both potable supplies and freshwater ecosystems.[11,12] Permits should be conditioned on demonstration that withdrawals will not compromise environmental flows necessary to sustain aquatic habitat under drought or peak demand scenarios. Discharge quality standards should account for the ecological sensitivity of receiving waters.

12.3. Noise regulation and acoustic habitat protection

Applying WHO Environmental Noise Guidelines[31] to data centers by setting maximum allowable noise levels at sensitive receptors, especially at night, and requiring noise impact assessments during permitting would protect both human communities and wildlife. A-weighting standards should be supplemented by C-weighting or other low-frequency-sensitive metrics. Acoustic setbacks from both residential areas and ecologically sensitive habitats (breeding sites, wildlife corridors, and wetlands) should be incorporated into siting criteria.[2,14]

12.4. Land-use planning and habitat conservation

Siting guidelines should prioritize previously developed or degraded land over greenfield sites, incorporate ecological connectivity assessments, and require habitat mitigation plans for unavoidable conversions. Stormwater management requirements should address the hydrological disruption caused by large impervious campuses. Heat island mitigation through landscape design, reflective surfaces, and green infrastructure can reduce both local ecological stress and facility cooling demand.

12.5. Sustainability impact assessment and monitoring

The Federation of American Scientists[5] recommends that state agencies conduct health impact assessments before and after data center construction. Expanding this framework to encompass full sustainability impact assessments, including ecological, hydrological, acoustic, energy-system, and socioeconomic dimensions, would provide a more complete picture. Requiring operators to report emissions, water use, noise levels, land-use changes, grid-interconnection needs, and projected ratepayer effects in standardized formats would facilitate ongoing accountability. Lifset *et al.*[4] show why permitting should account for off-site grid and transmission impacts as local environmental concerns rather than treating them as separate utility-planning matters. The Dominici Lab analysis of the Pittsylvania County proposal[21] demonstrates that rigorous impact assessment during permitting can influence infrastructure decisions in ways that protect both public health and ecological integrity.

12.6. Sustainability justice safeguards

Integrating environmental justice screening tools into siting and permitting can prevent concentrating new facilities in communities already overburdened by pollution or infrastructural deficits.[2,3,5,6] Sharing economic benefits, such as tax revenues and infrastructure investments, meaningfully with affected communities is essential for equity. Gour *et al.*[2] emphasize the need for coordinated governance across energy, water, noise, land-use, and communications domains, with structured community participation in siting decisions. Consistent with the procedural and recognition dimensions discussed in **Section 8**, this participation should be early, adequately resourced, and backed by access to operational data and by mechanisms, such as community benefit agreements and independent monitoring, that give affected residents genuine influence over outcomes rather than a purely advisory role.

12.7. Digital sufficiency and demand-side governance

A sustainability perspective also requires attention to demand. Digital sufficiency, parallel to energy sufficiency in the sustainability literature, asks whether every computational workload currently consuming resources is socially necessary or ecologically justifiable. Training ever-larger AI models, mining cryptocurrency, and streaming high-definition content all carry ecological costs that are currently externalized. Thomson[15] describes cryptocurrency mining as an energy-commons problem, a useful warning for AI infrastructure: if demand is governed only by private returns, the environmental and public-health costs of computation can be shifted onto host regions and ratepayers. Sinistore *et al.*[42] frame this tension

usefully, noting that AI holds the potential to optimize resource use and reduce emissions in other sectors, but only if the environmental burdens of enabling AI itself, including server manufacturing, energy consumption, and land conversion, do not outpace those gains. Berger[48] reinforces this concern through a case study of U.S.-based hyperscalers, showing that the clustering of AI-oriented facilities in regions like Northern Virginia is placing growing pressure on local electric grids and complicating clean energy planning. While this article does not advocate specific demand-side restrictions, it notes that supply-side efficiency improvements alone are unlikely to offset the projected growth in data center energy and water demand.[7] Sustainable digital infrastructure policy must address both how we compute and how much we compute.

13. Conclusion

Large data centers are central to digital infrastructure, but their ecological sustainability consequences have only recently begun to receive systematic scholarly attention. Viewed through a sustainability lens that integrates atmospheric, hydrological, acoustic, terrestrial, and social dimensions, the evidence is more concerning than carbon-centered analyses alone suggest. Data center expansion is already contributing to modeled atmospheric pollution burdens, with institutional analyses projecting substantial health damages under continued growth scenarios.[5,6,16] Water consumption at scales comparable to those of small municipalities may intensify freshwater stress in basins already under pressure, although direct ecological attribution studies remain unavailable.[11,12] Researchers have only begun to study the additional pressures of chronic industrial noise, land conversion, habitat fragmentation, and urban heat island intensification.

Tao and Gao's[1] call for empirical research remains urgent. There are no large cohort or quasi-experimental studies directly linking proximity to data centers with specific ecological or health outcomes, and many exposure pathways are inferred from analogs. Policymakers and planners do not need perfect evidence before adopting precautionary measures consistent with existing knowledge. In parallel, targeted research integrating environmental monitoring, ecological assessment, health data, and systems modeling can refine estimates and inform more precise interventions.

The planetary boundaries framework identifies levels of pressure beyond which the risk of large-scale, abrupt, or irreversible environmental change increases substantially. A single infrastructure sector that pressures the climate system, the freshwater cycle, biogeochemical flows, biosphere integrity, and the land system cannot be managed sustainably through piecemeal regulation of individual pollutants. It requires integrated governance informed by ecological science and guided by intergenerational and intragenerational equity.

As AI and digital services expand, decisions about how and where data centers are built, powered, cooled, and governed will shape climate trajectories, economic opportunities, the ecological integrity of landscapes, and the well-being of host communities. To make digital infrastructure ecologically sustainable and just, it is essential to incorporate sustainability science and ecological expertise into data center governance as design constraints rather than as afterthoughts.

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Appendix

Search protocol

(i) Databases and platforms: Web of Science Core Collection, Scopus, PubMed, and Google Scholar. Because Google Scholar does not support the full Boolean syntax used elsewhere, the first 200 results returned by relevance for each topical string were screened.

(ii) Coverage and dates: Publications dated January 1, 2009 to April 30, 2026. Final searches were completed on April 30, 2026, and every URL for a web-based source was confirmed live on that date.

(iii) Language: English only.

(iv) No restriction was applied to country, publication type, or study design beyond the screening criteria stated below.

(v) Search strings: A common population block was combined in turn with each of five topical blocks. Population block: ("data cent*" OR "datacent*" OR "hyperscale comput*" OR "cloud comput* facilit*"). Air quality: AND ("air pollution" OR "particulate matter" OR "PM2.5" OR "nitrogen oxide*" OR "NOx" OR "sulfur dioxide" OR "diesel generator*" OR "backup generator*" OR "acid deposition" OR ozone). Water: AND ("water use" OR "water consumption" OR withdrawal* OR cooling OR "cooling tower" OR "environmental flow*" OR aquifer OR groundwater OR "thermal discharge" OR blowdown). Noise: AND (noise OR "low-frequency noise" OR infrasound OR "sound level*" OR acoustic OR "acoustic ecology"). Land: AND ("land use" OR "land-use change" OR "habitat fragmentation" OR connectivity OR impervious OR "urban heat island" OR stormwater). Equity and governance: AND ("environmental justice" OR equity OR "sacrifice zone*" OR siting OR permitting OR "community benefit*" OR ratepayer* OR "planetary boundar*").

(vi) Supporting analogous literature: Where a mechanism could be evaluated only by analogy, the corresponding primary literature was searched separately, without the population block, using the same topical terms restricted to reviews and syntheses: for example ("flow alteration" OR "environmental flow*") AND "ecological response*"; "anthropogenic noise" AND (wildlife OR birds OR amphibian* OR bats); "habitat fragmentation" AND (biodiversity OR connectivity). Sources retrieved in this way support claims marked inferred in Table 1.

(vii) Screening and selection: Titles and abstracts were screened by a single reviewer against three criteria: the source addresses an environmental, ecological, or health consequence of data centers, or supplies analogous evidence used to interpret such a consequence; it reports empirical data, a quantitative model, a legal or policy analysis, or a synthesis; and its full text is retrievable. Records passing the screen were read in full and retained where they supported a specific claim. Reference lists of retained sources were checked for further material, and forward citation searching was carried out in Google Scholar for the most central sources.

(viii) Gray literature: A report, guideline, or dataset was treated as authoritative only where the issuing body is a government agency, an intergovernmental organization, a university research unit, or an established research institute, and where the document states its data sources or method. Preprints were excluded. Where a source first identified as a preprint had since been published in peer-reviewed form, the published version was substituted; where it had not, the claim was removed or attributed to an authoritative analysis that had itself adopted the estimate, which is then cited as the source of the figure.

(ix) Verification: Each retained record was checked against the publisher record for authorship, title, year, volume, page range, and DOI, and each claim in the manuscript was checked against the text of the source cited in its support. Where a cited source did not contain the claim attributed to it, the claim was withdrawn or re-attributed to the primary document. Institutional news items and press releases were replaced by the underlying technical report wherever one exists.

Table A1. Operationalization matrix for the five impact pathways

Pathway and mechanism	Indicator	Unit	Spatial scale	Temporal scale	Candidate data source	Expected direction of effect	Tier	Principal confounders
Atmospheric: on-site generators	Ambient $PM_{2.5}$ and NO_2 at nearest receptors	µg/m³; ppb	0–5 km from fenceline	Hourly; annual mean	Regulatory monitors; calibrated sensor networks; state permit and emissions inventories	Rises with generator runtime and with campus density	M→E	Traffic, other permitted sources, meteorology, wildfire smoke
Atmospheric: grid supply	Marginal emissions attributable to campus load	t/y $PM_{2.5}$, NO_x, SO_2	Balancing authority	Hourly dispatch; annual	EIA generation data; EPA emissions monitoring; marginal emissions services	Rises with load; falls with clean firm supply	M	Dispatch attribution assumptions, interregional trade, plant retirements
Freshwater: withdrawal	Consumptive withdrawal as share of reach low flow (Q95) or basin renewable supply	%	Sub-basin (HUC-8 or finer)	Monthly; drought years	Utility and permit records; stream gauge networks; operator disclosure	Rises with evaporative cooling and campus scale	E/I	Agricultural and municipal demand, drought, reservoir operation
Freshwater: aquatic response	Wetted width, water temperature, fish and macroinvertebrate indices	m; °C; index	Reach, upstream and downstream	Seasonal; multi-year	Field survey; state biomonitoring programs	Declines as base flow falls	I	Land-use change, climate variability, other abstractions, point-source discharge
Freshwater: discharge	Conductivity, temperature, chloride at outfall	µS/cm; °C; mg/L	Outfall to 1 km downstream	Continuous; seasonal	Discharge permit monitoring; utility records	Rises with blowdown volume and cycles of concentration	E	Road salt, wastewater effluent, baseflow variation
Acoustic: exposure	L_{Aeq} and L_{Ceq}, plus third-octave levels below 250 Hz, at receptors	dB(A); dB(C)	Property line to 1.5 km	Night (23:00–07:00); annual	Permit-required monitoring; independent community measurement	Rises with chiller and generator operation	E	Traffic, other mechanical plant, wind, terrain and screening
Acoustic: wildlife	Occupancy and vocal activity of noise-sensitive taxa	detections/night; occupancy	Noise gradient, 0–3 km	Breeding season; multi-year	Autonomous recording units; regional monitoring networks	Declines as sound level rises	I	Habitat quality, artificial light, land cover, detection bias
Land: conversion	Impervious surface area, including off-site infrastructure	ha; % of parcel	Campus plus 1 km buffer	Pre- and post-construction	National land-cover data; high-resolution imagery; permit records	Rises with campus, substation, and corridor footprint	E	Concurrent residential and commercial development
Land: connectivity	Effective mesh size; least-cost corridor resistance	km²; index	Landscape (county or ecoregion)	Decadal	Land-cover time series; connectivity models	Declines with cumulative campus development	I	Roads, agricultural conversion, model parameterization
Land: thermal	Land-surface temperature relative to reference land cover	°C	Campus plus 2 km	Summer, day and night	Satellite thermal imagery; local weather stations	Rises with waste-heat rejection and canopy loss	I	Regional heat waves, canopy differences, overpass timing
Justice: distribution	Population-weighted exposure by income, race, and prior burden index	µg/m³ per capita; ratio	Census block group	Annual	Screening tools; census estimates; modeled exposure surfaces	Exposure ratio above 1 in overburdened groups	M	Residential sorting, historical siting, boundary effects
Justice: procedure	Notice interval, completeness of disclosure, participation opportunities per application	days; count; index	Jurisdiction	Per application	Planning records; permit dockets; meeting minutes	Shorter notice and thinner disclosure where local capacity is low	E	Variation in state law, project size, media attention

Notes: The evidence tier indicates the status of the relationship that each indicator is intended to test: E, established; M, modeled; and I, inferred. M→E indicates a quantity currently estimated through modeling that could be established through direct measurement; E/I indicates a relationship for which the pressure component is established but the ecological outcome remains inferred. Abbreviations: AI: Artificial intelligence; EIA: Energy Information Administration; EPA: Environmental Protection Agency; HUC: Hydrologic unit code; NO_2: Nitrogen dioxide; NO_x: Nitrogen oxides; $PM_{2.5}$: Fine particulate matter with an aerodynamic diameter of 2.5 µm or less; SO_2: Sulfur dioxide.

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