REVIEW

Climate change and its implications for kidney health

David S. Goldfarb[a,b] and Anuj A. Patel[a]

Purpose of review
Extremes of weather as a result of climate change are affecting social, economic and health systems. Kidney health is being threatened by global warming while treatment of kidney disease is contributing to increasing resource utilization and leaving a substantial carbon footprint. Improved physician awareness and patient education are needed to mitigate the risk.

Recent findings
Rising temperatures are changing kidney disease patterns, with increasing prevalence of acute kidney injury, chronic kidney disease and kidney stones. These issues disproportionately affect people suffering from social inequality and limited access to resources.

Summary
In this article, we review the effects of climate change on kidney stones, and acute and chronic kidney injury. Finally, we discuss the impact of renal replacement therapies on the environment and proposed ways to mitigate it.

Keywords
acute kidney injury, chronic kidney injury, climate change, green dialysis, nephrolithiasis

INTRODUCTION

Climate change poses a significant threat to the well being of people around the globe, with the potential to undermine decades of progress made in global health. Growing populations, expansion of industrialization and urbanization have caused increased greenhouse gas emissions including CO_2 and methane [1]. As a result, the global temperature has increased to the point that 2023 was the warmest year in hundreds of thousands of years [2▪]. Even if all the emissions are stopped immediately, clearly not an imminent occurrence, the global temperature will continue to increase by 0.2–0.5°C over the next decade [3]. Increases in extreme events like drought, heat waves, floods, storms, and increased migration, and survival of pathogens are ways in which rising ambient temperature will adversely affect global health [4]. According to WHO between 2030 and 2050, climate change is anticipated to cause roughly 250 000 additional deaths per year, from infectious diseases and food shortages alone [5]. Temperature-related mortality is expected to rise at least until 2050 [4,6]. This phenomenon will cause significant stress to the public health infrastructure and certainly the supply chain, the relative failure of both of which was seen during the coronavirus disease 2019 (COVID-19) pandemic. Given its broad impact, physicians will have an important role to play in dealing with the consequences of climate change. The deleterious effects of climate change on cardiovascular disease, respiratory disease and infectious disease have been widely reported. In this article we attempt to review the consequences of climate change on kidney health.

EFFECTS OF CLIMATE CHANGE ON KIDNEY STONES

The prevalence of urinary stone disease (USD) is increasing, with the most recent estimate being that 1 in 11 people in the United States will have at least

[a]Division of Nephrology, NYU Langone Health and NYU Grossman School of Medicine and [b]Nephrology Section, New York Harbor VA Healthcare System, New York, New York, USA

Correspondence to David S. Goldfarb, MD, Professor of Medicine and Physiology, NYU Grossman School of Medicine, Nephrology Section/111G, New York Harbor VA Healthcare System, 423 E. 23 St., New York, NY 10010, USA. Tel: +1 212 686 7500 x3877; fax: +1 212 951 6842; e-mail: david.goldfarb@nyulangone.org

Curr Opin Urol 2024, 34:000–000

DOI:10.1097/MOU.0000000000001197

KEY POINTS

- Global warming is an emerging threat to kidney disease.
- There is emerging evidence linking exposure of ambient heat to increased incidence of nephrolithiasis, acute kidney injury and chronic kidney disease.
- People from poor socio-economic backgrounds and countries with limited resources will bear the greatest burden of climate change.
- Increased awareness among physicians, patient education and urgent attention of policy makers are needed to mitigate the impacts of climate change on kidney health.

one stone in their lifetime [7]. The economic burden of nephrolithiasis is immense, with annual direct medical cost of $10 billion, based on 2006 NIH data [8]. Even though the reasons for increased prevalence of USD are multifactorial, one cannot ignore its parallel trend with rise in global temperature. It is postulated that with increase in ambient temperature, insensible losses from sweat increase, resulting in a rise in vasopressin secretion and lower urinary volume. In turn, that urinary concentration will be associated with higher urinary supersaturation of calcium oxalate, calcium phosphate and uric acid [9]. Variation in geographic areas with higher prevalence of USD has been observed for many years. The prevalence of USD in the US population living in the south, known as "the stone belt," is higher compared to the north [10]. That phenomenon is attributed to greater ambient temperature. The association of heat and USD from west to east was found to be ambiguous [9]. A model that predicts northward expansion of the stone belt resulting from the progressive northward increase in ambient temperature predicts roughly an additional 1.6–2.2 million lifetime cases of USD by 2050, representing up to a 30% growth in some areas [11]. Similar trends are noted globally.

People living in cities are at higher risk of heat exposure as cities constitute urban heat islands (UHI). UHIs result from a lack of vegetation, reducing shade and preventing cooling effects of vaporization, as well as features of urban architectural density, and the nighttime radiation of heat from asphalt and concrete [12]. The result is that higher temperatures occur in cities than in surrounding rural areas, particularly at night. We have suggested that the 20th century's worldwide migration from rural to urban settings may in part explain the global rise in kidney stone prevalence [13]. The effects of such are likely to be of greater magnitude in people of lower socioeconomic status and minority groups, as they tend to live in hotter neighborhoods [14]. Some data demonstrate that the prevalence of USD is rising faster in Black than in non-Black populations [7]. We have hypothesized that this effect is due to greater heat exposure attributable to racist US housing policies (redlining) of the early 20th century [15]. USD thus serves as a prime example of an environmental health disparity.

Given the anticipated burden of changing environment on USD, it is imperative for public health measures to consider these associations. It is also important to recognize social trends and that this burden will be considerably higher in individuals of lower household incomes and minoritized populations. Urologists and nephrologists will play an important role in educating all patients on measures to mitigate the risk of USD. In addition to emphasizing the routine measures to reduce risk of recurrence of kidney stones, we should also talk to our patients about climate change in simple language [16] (Fig. 1). We now include the contents of Fig. 1 in our kidney stone handout for patients. Increasing fluid intake has always been the first step in stone prevention; that heat exposure may make our routine advice about prophylaxis obsolete is something for lithologists to consider.

It is important to note that a small part of the mitigation of greenhouse gas emissions would be an alteration of the global diet in a way that is consistent with USD prevention. Cattle raised for beef produce significant amounts of both CO_2 and methane, more so than any other food product. Reducing ingestion of animal protein, and emphasizing consumption of a plant-based diet, are both strategies that can diminish urinary risk factors for kidney stone formation. We therefore endorse our colleagues' call for an alignment of patient and planetary health [17▪]

EFFECTS OF CLIMATE CHANGE ON ACUTE KIDNEY INJURY

Acute kidney injury (AKI) is defined by rapid loss in kidney function (within hours to days) which is defined by a rise in serum creatinine concentration and often reflected by a decrease in urine volume. The causes of AKI are divided into three categories and include prerenal, renal and postrenal or obstructive kidney injury; these first two of three have been implicated in AKI due to heat exposure. The prerenal category includes hypo perfusion states like shock and extracellular fluid volume depletion causing neuro-hormonal changes leading to decreased glomerular filtration rate. Renal AKI is often the result

FIGURE 1. Five simple messages about global warming; a quick way to engage patients into a conversation about climate change [40].

of acute ischemic tubular injury (ATI), often called acute tubular necrosis or ATN in the past. Heat exposure has been implicated in causing ATI, but not other kidney injuries such as glomerulonephritis or interstitial nephritis. The incidence of AKI is rising globally, which is alarming due to its associated morbidity and mortality [18].

AKI is one of the manifestations of kidney injury due to heat. Several studies have shown a dose-dependent relationship between heat exposure and kidney-related emergency department (ED) visits [19,20▪]. In a study done across New York State examining ED data from 2005–2013, the risk of kidney-disease related emergency room visits following extreme heat exposure was 1.7–3%, with the strongest association being for AKI [20▪]. Older people (age > 65 years), children, pregnant women, outdoor workers, athletes and patients with preexisting conditions were at highest risk [21–23].

The mechanisms through which heat leads to AKI are multifactorial and depicted in Fig. 2 [24]. It is postulated that heat stress leads to increases in vasopressin secretion and activation of the renin–angiotensin–aldosterone axis, likely due to extracellular fluid volume loss which in turn leads to renal artery vasoconstriction and decrease in cortical blood flow where most glomeruli are located. The dwindling O_2 supply results in decreased ATP, stimulating a cascade of inflammatory responses resulting in AKI. Hyperosmolality also leads to an increase in the polyol-fructokinase pathway resulting in an increased amount of fructose, causing oxidative stress, and further amplifying kidney injury [24].

Preventing hyperthermia and replacing fluid loss are the only two major ways to mitigate risk of AKI. Administration of oral rehydration solutions would be appropriate, and for patients brought to emergency rooms and hospitals, intravenous crystalloid should be administered. To our knowledge, there are no other medications that can be used to prevent or improve heat related AKI.

EFFECTS OF CLIMATE CHANGE ON CHRONIC KIDNEY DISEASE

In recent times epidemics of chronic kidney disease of unknown etiology (CKDu) have been described worldwide, particularly in countries most affected by climate change, in equatorial locations [25]. The first instance of these reports was in the 1990s when clinicians in Central America noted end stage kidney disease (ESKD) in young men working in sugar cane fields [26]. These affected patients otherwise did not have any obvious cause of CKD [26]. Clinical features included absence or minimal proteinuria or leukocyturia, and often the presence of hyperuricemia [26]. The histological findings of kidney biopsies on these patients showed chronic interstitial disease, interstitial fibrosis and tubular atrophy [26]. These findings have led to the disorder also being called Chronic Interstitial Nephritis in Agricultural Communities, or CINAC [27]. CKDu is now reported in numerous agricultural communities located in hot, humid regions worldwide [25]. Initial concerns were that CKDu might be from exposure to agrochemicals such as paraquat, pesticides or heavy

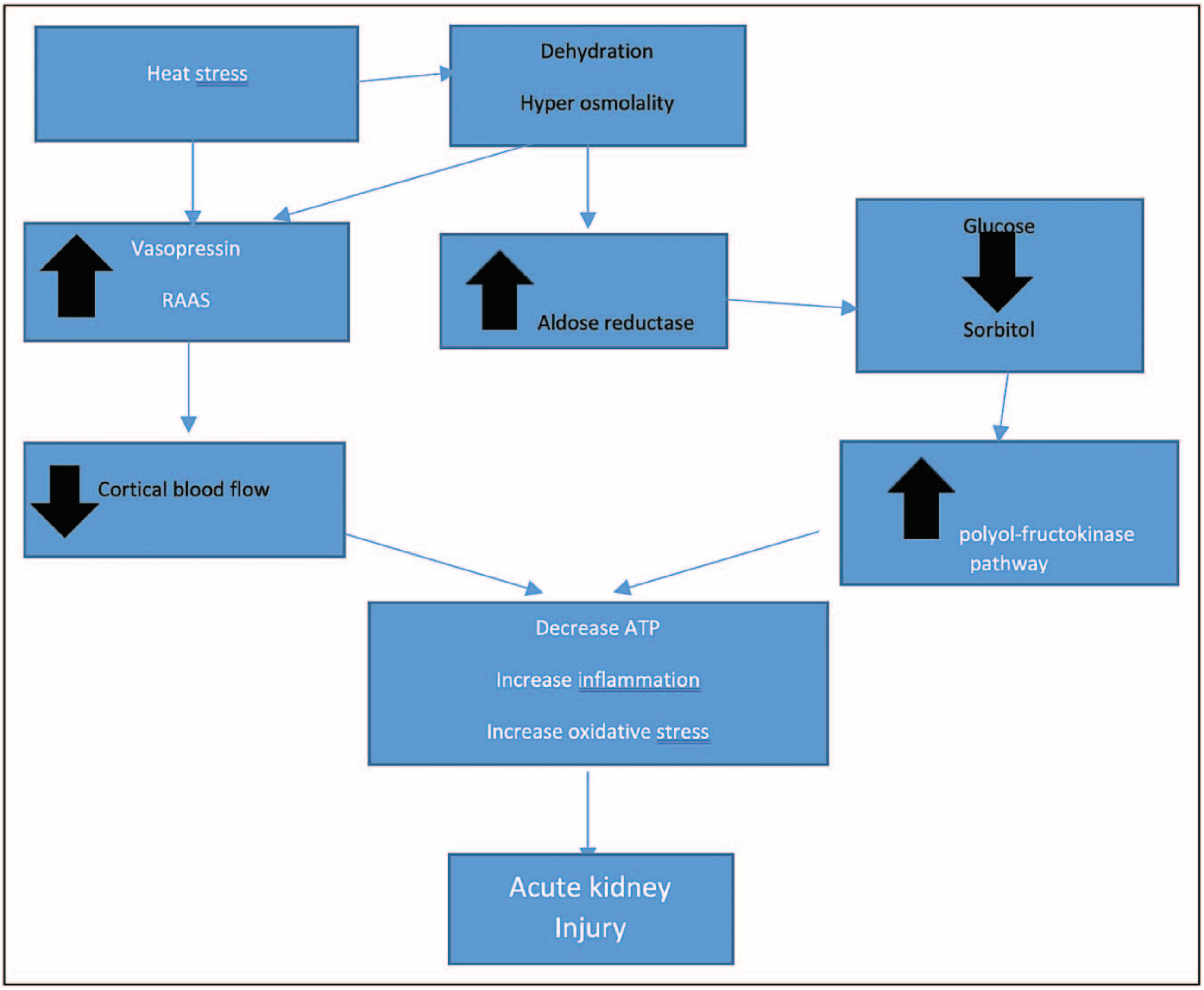

FIGURE 2. Adapted from Chapman C, Johnson, BD, Parker MD, *et al.* Kidney physiology and pathophysiology during heat stress and the modification by exercise, dehydration, heat acclimation and aging. Temperature (Austin). 2021;8:108–59. Potential mechanisms by which heat stress can cause AKI. RAAS, renin–angiotensin–aldosterone axis; ATP, adenosine triphosphate [24].

metals [27]. However, absence of this disease in patients working in sugar cane fields at higher altitudes, where the climate is cooler, and the presence of this syndrome in patients with other occupations, weaken this argument [25,28]. It is possible that toxins could be a contributing factor. Regardless of the many potential contributors, the one common variable that ties these affected communities together remains working and living in hot climate. In fact, most of the affected regions are the hottest regions of those countries [25]. Repeated injury from heat, dehydration, subclinical rhabdomyolysis and increased core temperature leading to uricosuria are thought to be among the possible mechanisms causing CKDu [26]. Glaser *et al.* [25] make the case for this phenomenon to be called *heat stress nephropathy*, and suggest that it might be the first epidemic resulting from global warming.

In addition to being implicated as one of the causes of CKD, there is emerging evidence that heat exposure can cause progression of other underlying etiologies of CKD. DAPA-CKD was one of the groundbreaking international placebo-controlled clinical trials of recent times that showed patients with CKD, regardless of etiology, had significantly lower risk of ESKD or death from renal or cardiovascular cause with dapagliflozin, an inhibitor of sodium-glucose transporter 2 (SGLT2i) compared to placebo [29]. *Post hoc* analysis of this trial showed association between heat and accelerated decline in estimated glomerular filtration rate (eGFR) [30■■]. The estimate was that a loss of 3.7 ml/1.73 m^2 of GFR per year was attributable to heat. The association was also found to be dose-dependent with greater heat exposure accounting for greater decline in GFR [30▪▪].

In addition to its contribution to global warming, air pollution is also emerging as a major global health risk factor. The link between air pollution and global warming is that both are the result of burning of fossil fuels. Numerous epidemiological studies have previously linked air pollution to disease of the respiratory and cardiovascular systems [31]. There is a growing body of evidence that links PM 2.5 and CKD. Inhaled particulate matter (PM) has been used as a proxy for air pollution, described by their diameter in microns: <0.1, <2.5, and 2.5–10. The smaller the size of PM, the greater its deleterious effects [32]. PM 2.5 contributes to roughly 8.5 million deaths per year globally [33]. A recent study found that exposure to higher annual average PM 2.5 was associated with higher levels of albuminuria and higher risk of CKD in a community based cohort [34]. Similar findings were reported in China [35]. Possible mechanisms accounting for these findings include the possibility that PM are absorbed by alveoli and make their way to the kidney, where they cause inflammation. Alternatively, it may be that inhaled PM 2.5 cause inflammation in the airways, leading to distant effects in other organs, including the kidneys.

The overall evidence suggests that climate change and its effects are important risk factors for CKD. Developing countries, and people of lower socioeconomic status, will be at significantly higher risk, further widening healthcare disparities and inequities. Urgent attention needs to be drawn, and policies created by stake holders, to address knowledge gaps and mitigate these risks.

GREEN(ER) DIALYSIS

The natural progression of CKD is to ESKD requiring renal replacement therapies (RRT). ESKD incidence and prevalence in the USA are projected to increase through 2030 [36]. Dialysis modalities, whether

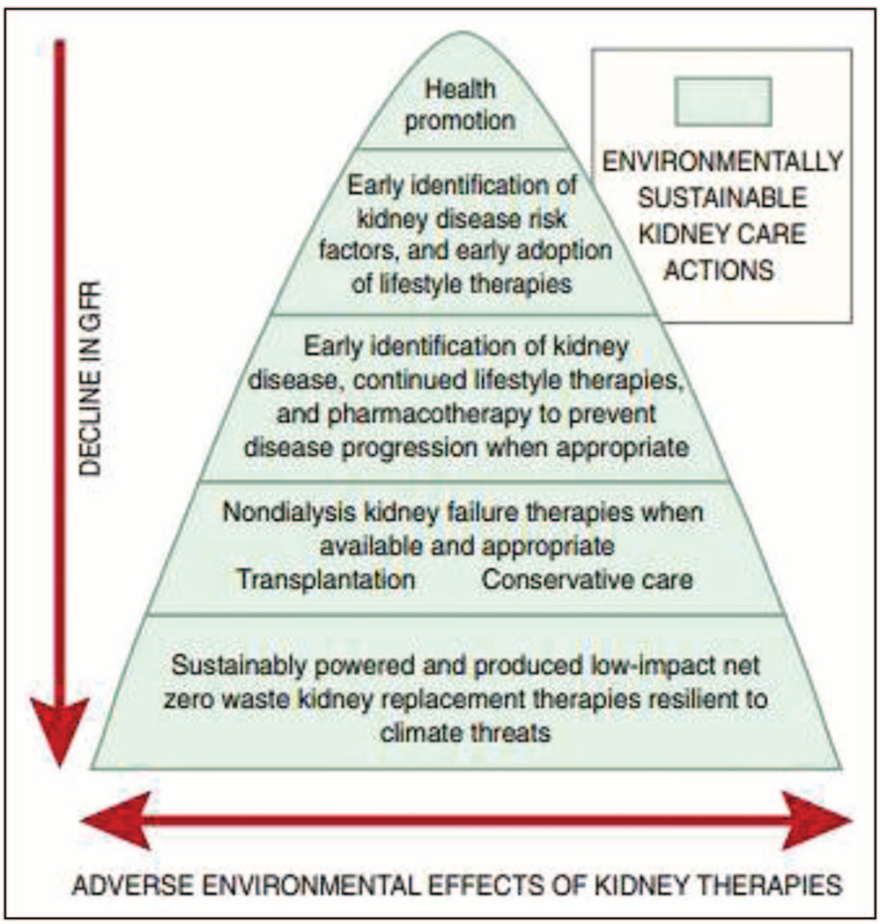

FIGURE 3. From Stigant CE, Barraclough KA, Harber M, *et al.* Our shared responsibility: the urgent necessity of global environmentally sustainable kidney care. Kidney Int. 2023;104:12–5. Framework of environmentally sustainable quality kidney care. GFR, glomerular filtration rate. Used by permission [39].

hemodialysis (HD) or peritoneal dialysis (PD), are among the most resource-consuming medical interventions. Water, power consumption and plastic wastage generated with RRT are associated with a significant carbon foot print. HD uses roughly 500 l of water per treatment [37]. With patients averaging three treatments per week for a total of 156 treatments/year, dialysis uses 80 000 l of water/patient/year [37]. Regarding plastic waste, 2.5 kg of single use plastic waste is discarded to landfill per treatment of HD and 1.5 kg with each treatment of PD [37]. In USA 8% of CO_2 emission is generated from the healthcare sector with dialysis constituting one of the most polluting medical interventions [37]. In the past decade the awareness of a need to strike a balance between the survival benefit of RRT and its associated environmental harms has increased among nephrologists. Multiple strategies including recycling reverse osmosis reject water, utilizing energy efficient HD machines and renewable sources of energy, reducing dialysate flow rates and optimal waste management are all strategies that have been proposed. Some of these programs are now being implemented [38]. However, significant work still remains to make dialysis green(er).

The International Society of Nephrology has begun to address these complex issues by developing the GREEN-K initiative: Global Environmental Evolution in Nephrology and Kidney Care [39]. The group is composed of representatives from many of the international nephrology societies. Its mission is to focus attention on education, sustainable clinical care, and advances toward environmentally sustainable innovations, procurement, and infrastructure. The GREEN-K initiative proposes that a "hierarchical patient-centric approach that permits climate change mitigation and adaptation is necessary" (Fig. 3). The figure demonstrates different strategies addressing people at varying stages of CKD.

CONCLUSION

"*Climate change is here. It is real. Experts agree. Its bad. There is hope*" [40]. Climate change is a global threat with its wide implication on health. It is changing kidney disease patterns and affecting vulnerable individuals of the society. The prevalence of USD, AKI, and CKD are expected to increase. The care of these kidney diseases are among the most resource-consuming medical interventions. Ultimately, in the distant future, reducing the progression of CKD to ESKD, and promoting transplantation instead of RRT will be greener approaches to these problems. Until then, we need to spread awareness, drive appropriate policies and protect the planet for generations to come.

Acknowledgements

None.

Financial support and sponsorship

None.

Conflicts of interest

Goldfarb: Owner: Moonstone Nutrition, Inc.; Consultant: Alnylam, NovoNordisk, Arthrosi, Lilac Pharma; Research funding: Travere, NovoNordisk.

REFERENCES AND RECOMMENDED READING

Papers of particular interest, published within the annual period of review, have been highlighted as:
▪ of special interest
▪▪ of outstanding interest

1. Yoro K, Daramola, MO. CO_2 emission sources, greenhouse gases, and the global warming effect. Elsevier; 2020.
2. ▪ Berkely Earth Global Temperature. Available at: http://berkeleyearth.org/global-temperature-report-for-2020/

This website provides comprehensive data on global temperature and air pollution across the globe.

3. Matthews H, Zickfeld K. Climate response to zeroed emissions of greenhouse gases and aerosols. Nature Clim Change 2012; 2:338–341.
4. Zhao Q, Yu P, Mahendran R, *et al.* Global climate change and human health: Pathways and possible solutions. Eco Environ Health 2022; 1:53–62.
5. World Health Organization. Available at: https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health.
6. Zhao Q, Guo Y, Ye T, *et al.* Global, regional, and national burden of mortality associated with nonoptimal ambient temperatures from 2000 to 2019: a three-stage modelling study. Lancet Planet Health 2021; 5:415–425.
7. Scales CJ, Smith AC, Hanley JM, *et al.* Prevalence of kidney stones in the United States. Eur Urol 2012; 62:160–165.
8. Cabo J, Gelikman DG, Hsi RS. The financial burden of nephrolithiasis and predictors of disease-specific financial toxicity. Urology 2023; 171:57–63.
9. Fakheri R, Goldfarb DS. Ambient temperature as a contributor to kidney stone formation: implications of global warming. Kidney Int 2011; 79:1178–1185.
10. Soucie J, Coates RJ, McClellan W. Relation between geographic variability in kidney stones prevalence and risk factors for stones. Am J Epidemiol 1996; 143:487–495.
11. Brikowski T, Lotan Y, Pearle MS. Climate-related increase in the prevalence of urolithiasis in the United States. Proc Natl Acad Sci USA 2008; 105:9841–9846.
12. Oke TR. The energetic basis of urban health. Q J Roy Meterol Soc 1982; 108:1–24.
13. Goldfarb D, Hirsch J. Urbanization and exposure to urban heat islands contribute to increasing prevalence of kidney stones. Med Hypotheses 2015; 85:953–957.
14. Hsu A, Sheriff G, Chakraborty T, Manya D. Disproportionate exposure to urban heat island intensity across major US cities. Nat Commun 2021; 12:2721.
15. Scotland K, Cushing L, Scales CD Jr, *et al.* Redlining has led to increasing rates of nephrolithiasis in minoritized populations: a hypothesis. Curr Opin Nephrol Hypertens 2023; 32:103–109.
16. Goldfarb D. Nephrologists should talk to their patients about climate change. Curr Opin Nephrol Hypertens 2024; 33:170–173.
17. ▪ Cole AP, Loeb S. Dietary and lifestyle recommendations that align patient and planetary health. Eur Urol Focus 2023; 9:869–872.

This review highlights how life style modifications can help reduce stone burden and reduce carbon footprint.

18. NH Lameire AB, D. Cruz J, *et al.* Acute kidney injury: an increasing global concern. Lancet 2013; 382:170–179.
19. Hansen A, Bi P, Ryan P, *et al.* The effect of heat waves on hospital admissions for renal disease in a temperate city of Australia. Int J Epidemiol 2008; 37:1359–1365.
20. ▪ Qu Y, Zhang W, Boutelle AM, *et al.* Associations between ambient extreme heat exposure and emergency department visits related to kidney disease. Am J Kidney Dis 2023; 81:507–516.

Case cross-over study that shows dose dependent relationship between heat and ED visits for kidney health

21. Sorensen C, Hess J. Treatment and prevention of heat-related illness. N Engl J Med 2022; 387:1404–1413.
22. Nerbass FB, Pecoits-Filho R, Clark WF, *et al.* Occupational heat stress and kidney health: from farms to factories. Kidney Int Rep 2017; 2:998–1008.

23. Meade R, Akerman AP, Notley SR, *et al.* Physiological factors characterizing heat-vulnerable older adults: a narrative review. Environ Int 2020; 144:105909.
24. Chapman C, Johnson BD, Parker MD, *et al.* Kidney physiology and pathophysiology during heat stress and the modification by exercise, dehydration, heat acclimation and aging. Temperature (Austin) 2021; 8:108–159.
25. Glaser JL, Rajagopalan B, Diaz H, *et al.* Climate change and the emergent epidemic of CKD from heat stress in rural communities: the case for heat stress nephropathy. Clin J Am Soc Nephrol 2016; 11:1472–1483.
26. Johnson R, Newman L. Chronic kidney disease of unknown cause in agricultural communities. N Engl J Med 2019; 380:1843–1852.
27. Holliday MW Jr, Majeti RN, Sheikh-Hamad D. Chronic interstitial nephritis in agricultural communities: observational and mechanistic evidence supporting the role of nephrotoxic agrochemicals. Clin J Am Soc Nephrol 2024; 19:538–545.
28. Sandra Peraza S, Aragon A, Leiva R, *et al.* Decreased kidney function among agricultural workers in El Salvador. Am J Kidney Dis 2012; 59:481–484.
29. Heerspink H, Stefánsson BV, Rotter RC, *et al.* Dapagliflozin in patients with chronic kidney disease. N Engl J Med 2020; 383:1436–1446.
30. ■■ Zhang Z, Heerspink HJL, Chertow GM, *et al.* Ambient heat exposure and kidney function in patients with chronic kidney disease: a posthoc analysis of the DAPA-CKD trial. Lancent Planet Health 2024; 8:225–233.

This post hoc analysis shows heat exposure leads to rapid EGFR loss in patients with established CKD.

31. Boogaard H, Walker K, Cohen AJ. Air pollution: the emergence of a major global health risk factor. Int Health 2019; 11:417–421.
32. Basith S, Manavalan B, Shin TH, *et al.* The impact of fine particulate matter 2.5 on the cardiovascular system: a review of the invisible killer. Nanometers (Basel) 2022; 12:2656.
33. Al-Aly Z, Bowe B. Air pollution and kidney disease. Clin J Am Soc Nephrol 2020; 15:301–303.
34. Blum M, Surapaneni A, Stewart JD, *et al.* Particulate matter and albuminuria, glomerular filtration rate, and incident CKD. Clin J Am Soc Nephrol 2020; 15:311–319.
35. Li G, Huang J, Wang J, *et al.* Long-term exposure to ambient PM2.5 and increased risk of CKD prevalence in China. J Am Soc Nephrol 2021; 32:448–458.
36. McCullough K, Morgenstern H, Saran R, *et al.* Projecting ESRD incidence and prevalence in the United States through. J Am Soc Nephrol 2019; 30:127–135.
37. Agar J. Dialysis and the environment: seeking a more sustainable future. Artif Organs 2019; 43:1123–1129.
38. Barraclough K, Agar JWM. Green nephrology. Nat Rev Nephrol 2020; 16:257–268.
39. Stigant CE, Barraclough KA, Harber M, *et al.* Our shared responsibility: the urgent necessity of global environmentally sustainable kidney care. Kidney Int 2023; 104:12–15.
40. Maibach E, Uppalapati S, Orr M, *et al.* Harnessing the power of communication and behavior science to enhance society's response to climate change. Annu Rev 2023; 51:53–77.

