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Research paper

The interplay of climate change and physical activity: Implications for cardiovascular health

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ABSTRACT

Cardiovascular disease (CVD) is one of the top contributors to global disease burden. Meeting the physical activity guidelines can effectively control and prevent several CVD risk factors, including obesity, hypertension and diabetes mellitus. The effects of climate change are multifactorial and have direct impacts on cardiovascular health. Increasing ambient temperatures, worsening air and water quality and urbanisation and loss of greenspace will also have indirect effects of cardiovascular health by impacting the ability and opportunity to participate in physical activity. A changing climate also has implications for large scale sporting events and policies regarding risk mitigation during exercise in hot climates. This review will discuss the impact of a changing climate on cardiovascular health and physical activity and the implications for the future of organised sport.

1. Introduction

Cardiovascular disease (CVD) is the leading contributor to global mortality and disease burden for both men and women [1]. Physical inactivity is the fourth leading risk factor for global CVD mortality, behind hypertension (HTN), tobacco use, and hyperglycaemia [2]. Physical activity (PA) positively impacts blood pressure [3] and hyperglycaemia [4], thereby attenuating three of the top four CVD risk factors. An active lifestyle is considered the cornerstone of primary and secondary CVD prevention and treatment [5] and the World Health Organisation (WHO) recommends achieving adequate PA levels to reduce the risk of CVD [6].

One of the biggest challenges for optimising CV health by addressing physical inactivity will be climate change. Rapid urbanisation, increasing temperatures and worsening air quality have direct consequences on CV health and will contribute to the growing burden of CVD. Climate change will also make it harder to access outdoor areas and reduce opportunities for PA, which will worsen its effects on CV health. Together, this suggests that climate change will contribute to the global burden of CVD.

The global incidence of traditional CVD risk factors is rising and by 2050 there will be a shift in the top causes of global disease burden, from neonatal disorders and lower respiratory tract infections in 2021 to non-communicable, chronic diseases such as ischemic heart disease, stroke and diabetes [7,8]. This becomes even more apparent in developing countries, where the disease profile is shifting from infectious diseases and nutritional deficiencies to non-communicable ‘lifestyle’ diseases, namely CVD [9]. Developing countries will likely be disproportionately affected by climate change [10], partially because a large proportion of people in these regions rely on climate-sensitive activities such as agriculture, forestry and fisheries. Further, rising temperatures and worsening water quality will likely exacerbate pre-existing disparities in access to healthy and affordable food and clean water [10]. It will therefore become increasingly important for individuals to meet PA requirements to mitigate the increased risk and incidence of CVD in a changing climate. This narrative review will briefly explore the elements of climate change that influence CV health and it will describe the secondary effects of climate change on CV health by impacting PA levels as a modifiable risk factor for CVD.

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2. Drivers of climate change

2.1. Ambient temperature

World-wide trends show an upward shift in global wet bulb temperature index (Tw) distribution [11]. The average temperature of the earth's surface is approximately 1.5 °C warmer than the late 1800's (pre-industrial revolution) [12,13]. Each of the past four decades have been warmer than any preceding decade since record keeping began in 1850 and the last decade (2011–2020) was the warmest on record [12–14]. These increases in temperatures are driven by greenhouse gas emissions such as carbon dioxide, methane and nitrous oxide [15]. Increasing global temperatures result in melting ice caps and glaciers, rising sea levels and more frequent and severe extreme weather events [12].

2.2. Air quality

Fossil fuel combustion and smog are primarily responsible for increases in airborne particulate matter (PM) concentrations [16]. $PM_{2.5}$ (particles with a diameter < 2.5 μm) are most associated with negative health effects as they deposit deep into the alveoli of the lungs. WHO set a recommended annual average concentration of $PM_{2.5}$ of 5 $\mu g/m^3$ [17], but in 2021, no country in the world had $PM_{2.5}$ concentrations below this threshold [17]. It is projected that global mean $PM_{2.5}$ will increase annually by 0.43 $\mu g/m^3$, with large increases (>3 $\mu g/m^3$) over some areas, including Western Australia, North America and East Asia [18]. These increases in $PM_{2.5}$ are directly attributable to greenhouse gas-induced warming.

2.3. Urbanisation

Urbanisation is the permanent increase in the population of an area and the formation of cities. The United Nations predicts a 20 % increase in urban density to approximately 1.1 billion urban citizens by 2030, resulting in 70 % of the world's population living in cities [19]. Urban design determines how people move around cities. Cities without infrastructure for active travel or high urban sprawl promote car travel [20], thereby increasing air pollution and greenhouse gas emissions and reducing incidental PA [21]. In Australia (a car-centric country), domestic transport accounted for 84 % of greenhouse gas emissions (106,000 gigagrams of CO_2) in 2022–2023, in comparison to 9 % from aviation [22]. Compact cities with cycling and walking infrastructure have less vehicle-related energy consumption, air pollution, and a smaller ecological footprint [23]. Increasing urbanisation also may reduce the amount of greenspace in cities. Greenspace reduces land surface temperature [24] and PM [25], and increases ground water filtration, thereby reducing residual run-off and water pollution [26].

Rapidly expanding urbanisation has resulted in alterations to water infiltration and evapotranspiration. Impervious surfaces from built environments exacerbate surface water runoff [27], and high-density urban environments generate waste pollution at higher rates compared to their rural counterparts and contribute to compaction and sealing of natural soils [28]. Concentrations of microbial and pharmaceutical contaminants are higher in urban areas [29], and higher eutrophication rates and prevalence of pathogens such as *Cryptosporidium* are observed in areas of high-density populations [30].

Together, these drivers manifest as high ambient temperatures and poor air and water quality; all of which drive climate change. These factors have direct effects on the cardiovascular system (primary effects) and limit an individuals' ability and opportunity to perform PA, thereby further increasing CV risk (secondary effects). The remainder of this review will discuss how each of these factors impact CV risk and the secondary effects of each of these factors on recreational PA rates and larger organised sporting events.

3. The primary effects of climate change on CVD risk

3.1. Ambient temperature

Hyperthermia (e.g., core body temperatures >38.5 °C) causes a reduction in blood volume through excessive sweating and systemic vasodilation. Tachycardia, tachypnoea and vasodilation occur to compensate for this reduction in blood volume [31]. While this is a physiological response to cool the body, it can result in dehydration which further compounds a net loss of central vascular volume and increases blood viscosity, placing additional strain on the CV system [32]. A phenomenon called "cardiac drift" is observed when fluid loss is not replaced, characterised by decreases in stroke volume, cardiac output, arterial blood pressure, and compensatory increases in heart rate and total peripheral resistance [33]. Hyperthermia can lead to CV-related death; a 1 °C increase in temperature is associated with a 2.1 % increased risk of cardiovascular mortality, specifically from stroke, CHD, arrythmias and cardiac arrest [34].

The compensatory mechanisms described above (i.e., tachycardia, tachypnoea and vasodilation) are compromised in those with pre-existing CVD. Therefore, heat stress places an increased burden on these individuals and may exacerbate CV symptoms and disease progression, such as ischemia and atherosclerotic plaque disruption [32].

Not only will average temperatures increase with climate change, but the incidence, duration and severity of extreme weather events will also increase [35]. Extreme weather events are unexpected, severe or unusual weather and include heat waves, cold snaps and heavy rain [36]. They are typically defined as weather patterns that lie below the 10th, or above the 90th percentile of a probability density function, for a given location [36]. Heat waves (temperatures >90th percentile of their mean annual value for 0–4 consecutive days) will have the most pertinent effect on CVD risk. If the acute physiological response to hyperthermia becomes chronic due to sustained heat exposure (such as during heat waves), the pathophysiological implications include increased sympathetic activation, increased arterial pressure, systemic inflammatory responses, and coagulopathy changes which increase CV strain and can eventuate in CVD [37,38]. Heat stroke (core temperature > 40 °C [31]) is characterised by a reduction in central venous pressure and insufficient cardiac output and can result in multi-organ failure and death [31]. Heat waves increase the risk of CVD mortality by 11.7–21 %, with the risk increasing with increasing temperatures [34]. Given the projected increases in average temperatures and the incidence and severity of heat waves, it is reasonable to assume that the burden of heat on CVD morbidity and mortality will also increase.

3.2. Air quality

Long-term exposure of $PM_{2.5}$ is associated with the development and progression of CVD by causing endothelial dysfunction [39,40], systemic inflammation and oxidative stress [39,41], autonomic imbalance and arrythmias [41], and the progression of atherosclerosis [39]. Elevated environmental PM levels are associated with increases in CVD associated hospital admissions [42] and causes of death including heart failure, arrythmia, and cerebrovascular disease [43]. In particular, at-risk groups such as those with pre-existing CVD [42] are at higher risk of autonomic imbalance and arrythmias [41], and atherosclerosis [39], increasing CV strain and exacerbating disease progression. Specifically, there is a dose-response relationship between increasing $PM_{2.5}$ and CVD death, with a 10–24 % increased risk of CVD mortality for every 10 $\mu g/m^3$ increase in $PM_{2.5}$. WHO estimates 800,000 premature deaths per year attributable to long-term exposure to $PM_{2.5}$ [39]. It is projected that increasing PM concentrations will be attributable for additional 194,448 premature deaths every year as a result of climate change [18].

4. Secondary effects on CVD

4.1. Ambient temperature and physical activity

Exercise results in fluid loss and dehydration, which is exacerbated when exercising in the heat. A reduction in blood volume through sweating and systemic vasodilation increases cardiovascular demand and cardiac output cannot be sustained due to the competing demands for perfusion of vital organs and skeletal muscle blood flow [31]. If dehydration is combined with extreme environmental conditions, heat illness will occur more commonly and earlier in exercise. If exercise is started in an already hypo-hydrated state, the effects of cardiac drift are experienced more rapidly and can contribute to heat illness, regardless of aerobic fitness [44]. This is a concern, as exertional heat stroke remains the third leading cause of death in US athletes, after cardiac disorders and head and neck trauma [45].

As average temperatures and the incidence of extremely hot days increase, exercise opportunity will be limited for both organised sports and in the general population. Regarding organised sport, sporting organisations such as World Triathlon currently recommend that sport is cancelled or postponed when Tw exceeds 35 °C [46]. Similarly, Sports Medicine Australia (SMA) has various cancellation thresholds for sports that account for temperature and humidity, with lower temperature thresholds set as humidity increases [47]. SMA has different thresholds for different sports, according to exercise intensity and the clothing and equipment worn in combination with ambient heat and humidity.

In the general population, undertaking outdoor PA will become more difficult as environmental conditions worsen. Exercise in hot and humid conditions is subjectively harder, which may reduce motivation and deter individuals from participating in outdoor exercise. Subjective rating of perceived exertion (RPE), heart rate and lactate accumulation were higher, maximal oxygen consumption (VO_{2peak}) was lower and subjects had a lower affect when exercise was performed under hot conditions compared to thermoneutral conditions [48–50]. Together, this suggests that exercise capacity may be reduced and feel harder in hot conditions. Therefore, people will be less inclined to exercise when ambient temperatures and their risk of experiencing heat illness is increased.

4.2. Air quality and physical activity

Exercise increases ventilation rate and depth, potentially increasing an individual's exposure to PM when exercising in heavily polluted areas. It is unclear whether the well-documented positive effects of exercise are sufficient to counteract the negative effects of exposure to PM on the cardiovascular system. There is some evidence that exercising next to a busy road attenuated the beneficial effects of exercise on lung function and vascular reactivity that were observed when participants exercised in a traffic-free environment [51]. In this study, $PM_{2.5}$, ultrafine particles and black carbon were associated with arterial stiffness [51]. Similarly, there were significant, negative interactions between long-term $PM_{2.5}$ exposure and habitual PA on lung function, suggesting that increased PM intake may attenuate some of the benefits of habitual PA [52]. However, PA had beneficial effects on lung function across $PM_{2.5}$ quartiles [52], suggesting that PA should still be recommended to those living in areas of high PM concentrations. To support this, the harms of exercising in air pollution may only exceed the benefits of exercise after 1.5 h of cycling, or 10 h of walking per day in extreme levels of $PM_{2.5}$ [53]. The World Heart Organisation therefore recommend PA to everyone, regardless of geographical context or air pollution exposure [17]. To fully elucidate the harm/benefit trade-off between PA and exposure to PM among different populations more research is needed, particularly focusing on at-risk populations such as those with pre-existing CVD. Public messaging regarding exercise in PM is vital, as evidence suggests that increased PM concentrations discourage PA in Beijing [54] and the US [55].

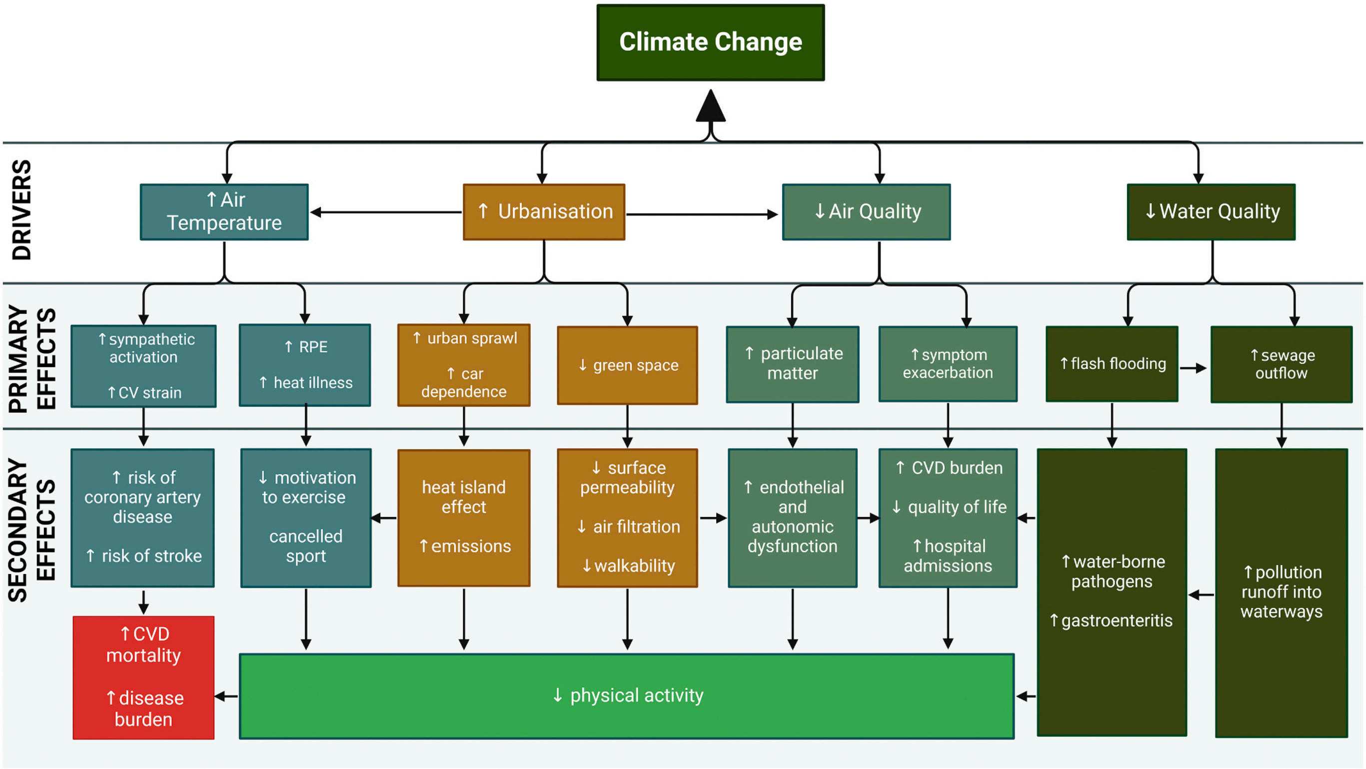

Fig. 1. Drivers of climate change and their direct (primary) and indirect (secondary) effects on cardiovascular (CV) mortality and burden of disease. *CVD: cardiovascular disease, RPE: rating of perceived exertion.*
Figure created with biorender.com.

4.3. Urbanisation and physical activity

Countries with large populations, rapid economic development and urbanisation report the highest national rates of CVD-related mortality from physical inactivity [48,56] compared to countries with high socioeconomic status, health literacy and national health programs [56]. This trend has implications for regions with poor socioeconomic status, high population density and poor health literacy and public health programs [57] such as East Asia and North Africa. These regions have the highest CVD mortality burden from physical inactivity [57] and are therefore likely to experience further disease burden as the effects of climate change progress. This suggests that as urbanisation and population density increase, public health programs and CVD health education will be vital to promote healthy living and attenuate the increased CVD risk in these regions.

The walkability and land area of cities directly impacts opportunities for active travel. Cities that are compact and conducive to active travel have higher rates of transport-related PA [21], and decreased rates of morbidity and mortality [23]. The incidence of modifiable risk factors for CVD is lower in compact, walkable cities such as Barcelona (32.7 %) and Girona (32.6 %) compared to spaced-out areas that rely on cars such as the Canary Islands (65 %) and Murcia (66.7 %) [58]. High-density living is associated with a lower risk of obesity, type 2 diabetes, blood pressure, body mass and waist circumference cross-sectionally [59,60], and people living in highly-walkable areas have significantly lower systolic blood pressure and are less likely to smoke [23]. This demonstrates that neighbourhood walkability has direct effects on modifiable CVD risk factors.

The loss of green spaces due to urbanisation will likely further inhibit the opportunity to exercise and contribute to the growing burden of CVD. Meta-analyses show that greenspace was significantly associated with lower odds of mortality from CVD, ischemic heart disease (IHD), cerebrovascular disease (CBVD) or stroke [61]. Distance from greenspace is also an important factor, with an increased risk of fatal and non-fatal CVD for those who live further away from parks [62]. This provides strong evidence that greenspace is beneficial for CV health and should be taken into consideration when planning neighbourhoods and cities. While the mechanisms behind this remain to be fully elucidated, mitigation of harmful exposure to heat and air pollution and the encouragement of PA are likely the main factors mediating this relationship [61].

4.4. Water quality and physical activity

Swimming, especially swimming in natural waterways is a highly attractive form of aerobic exercise as it is accessible and inexpensive. It is also suitable for people who are unable to complete land-based exercise and those without logistical or financial access to infrastructure such as public pools [63]. Water pollution and extreme rainfall will make it significantly harder for the population to meet its PA requirements for CV health by limiting the accessibility and safety of naturally occurring waterways. Areas of large-scale urbanisation have seen an upward trend in faecal bacterial concentrations of *Escherichia coli* (*E. coli*) and intestinal *enterococci* (*E. faecalis* and *E. faecium*) between 1911 and 2018 [64]. Since 2023, Victoria, Australia, has experienced a 600 % increase in cryptosporidiosis cases, a form of gastroenteritis caused by the *cryptosporidium* parasite [65]. This directly correlates with record low water quality in Victoria after a period of record high rainfall [66]. These rain falls resulted in public swimming pool closures and cancellations of exercise programs such as mid-week water aerobics and children's swimming lessons.

Fig. 1 outlines how each driver of climate change affects CV health directly (primary drivers) and indirectly via modifying PA levels (secondary effects).

5. Current strategies to minimise the effects of climate change and future directions

5.1. Circumventing heat illness in competitive sports

There are already many examples of how environmental conditions can change the landscape of competitive sport. One such example is the 2022 FIFA World Cup held in Qatar. Qatar is one of the hottest countries in the world, with average air temperatures exceeding 40 °C in the summer months. This raised concerns that athletes and fans were at an increased risk of heat-related illness. To address these concerns, the World Cup was moved from the traditional months of June and July (Qatar's summer months) to the winter months of November and December [67,68]. More controversially, organisers announced that that all stadiums would be air conditioned, which brought attention to the environmental impact of air conditioning large, open roof stadiums [67,68]. To minimise the environmental effects of the air conditioners, the organisers employed “spot cooling”, whereby the cooled air was directed only to the field and seats. This scenario highlights the problems with current strategies currently being employed to circumvent the effects of a changing climate. While athletes cannot be expected to compete in extreme heat, the electricity required to power these air conditioners and the release of refrigerant chemicals (which are potent greenhouse gases) directly contribute to climate change, compounding the problem.

Hot and humid conditions presented a similar problem at the Tokyo 2020 Summer Olympics and Paralympics [69]. All cases of heat-illness in athletes took place outdoors and there was a significantly higher incidence of heat-related illness when the Tw exceeded 28 °C [69]. Heat mitigation strategies for athletes including ice-vests, ice slurry drinks [70] and access to rooms with fans, ice baths and air conditioners before and after competition can reduce core body temperature, CV strain and enhance performance [31,71] and should therefore be considered for athletes competing in outdoor events, or at Tw >28 °C. The International Olympic Committee (IOC) recommends that athletes have more time to acclimatise before competition, which increases athletes' heat tolerance, reduces the risk of heat illness and increases performance in the heat [72,73]. Organisers should also introduce more breaks and opportunities for hydration and nutrition during competition, potentially alter the distance and duration of events and consider playing surface colour and materials and the amount of shade available to athletes and spectators [74].

There is a higher incidence of heat-related illnesses in wheelchair-bound athletes compared to other athletes, due to altered vasomotor control and impaired body temperature control [70]. Wheelchair-bound athletes with tetraplegia displayed greater thermal strain even in thermoneutral conditions (19–21 °C) and these athletes can reach core temperatures of >39.5 °C [75]. Despite this, wheelchair tennis is the only sport that has specific heat policies for wheelchair-bound athletes [76]. This is clearly an area that requires further attention from researchers and policy makers in a warming climate.

5.2. Strategies to combat air pollution

High population density and rapid economic expansion results in high volumes of industrial waste, and societal dependence on motor vehicles exacerbates this due to increasing vehicle exhaust emissions [77]. The amount of greenspace and the combination of planting proximity and choice of flora is an effective intervention for removing atmospheric PM. $PM_{2.5}$ concentrations are 9 % lower in woodland areas adjacent to urban areas in Shanghai [78], and trees in Beijing are responsible for removing 1261 metric tonnes of pollutants, including 772 metric tonnes of PM_{10} [79]. Carbon storage levels of mixed species woody greenbelts are estimated to retain up to 47.9 t of foliar dust emitted by 2.2 million annual vehicle passages along Highway No.1 in Taiwan [25]. This clearly demonstrates the efficacy of strategic planting

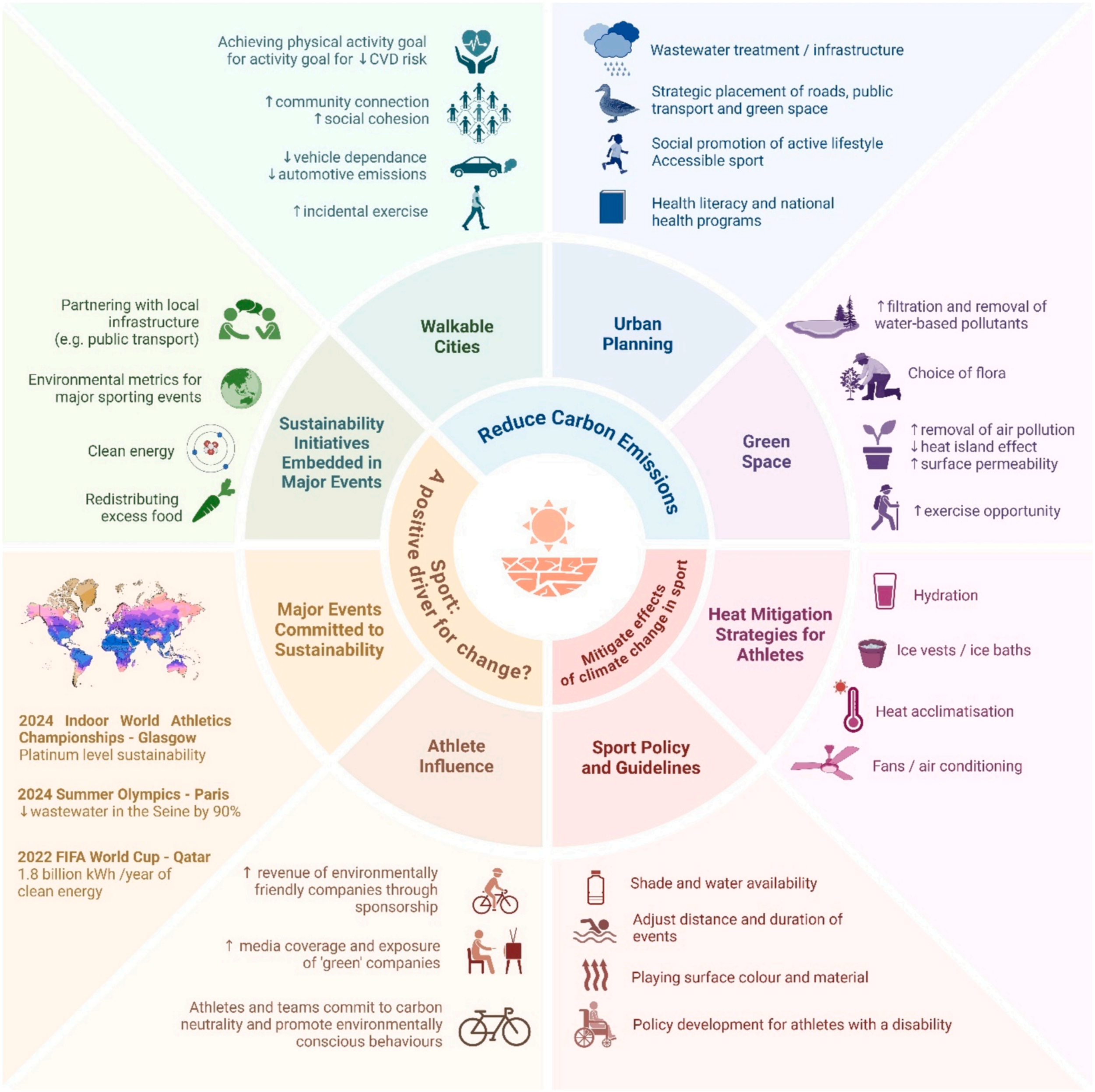

Fig. 2. Proposed approaches how environmental change may come about through sport and strategic urban planning. Due to increasing ambient temperatures due to climate change, athletes and sport policy makers should also be aware of the dangers of heat illness and strategies to combat increased core temperature and exercise-related heat illness. Figure created in biorender.com.

of trees to minimise PM and its effects on the environment and on individual CV health.

5.3. *Strategies to combat water pollution*

Urbanisation and overpopulation may also result in a deterioration of water quality. An example of this is the Seine in Paris, where the sewerage system combines storm water with sewage, discharging nearly 2 million m^3 into the river annually. Unprecedented rainfall increased *E. coli* levels to unsafe concentrations and resulted in the cancellation of two major Olympic test events in 2024. Concerns were also raised over the safety of holding outdoor swimming events in the Seine during the Paris 2024 Olympics, with the postponement of events due to poor water quality and athletes expressing concern for their health and well-being [80]. In 2015, the Seine cleanup proposal was a major component in the winning bid to host the 2024 Olympics [81], and improvements to upstream water treatment plants including the construction of a large water tank, the *Bassin d'Austerlitz*, were implemented [82]. The underground reservoir, designed to intercept and filter storm water runoff resulted in a 90 % reduction in the amount of untreated wastewater in the Seine from 2004 [83].

Water runoff can also be reduced through strategic placement and choice of vegetation. In a 9 m^2 asphalt plot, planting a single *Acer campestere* tree can reduce surface-water runoff by 62 % [84], and replacing asphalt with grass reduced water runoff by 99 % [85]. Where the use of vegetation is impossible or impractical, semi-permeable materials such as permeable interlocking concrete pavers can achieve flow rates of up to 2450 cm/h [86]. These pavers effectively remove pollutants from water, and show a 46 % reduction in combined sewerage, a 50–60 % reduction in particulate-bound metals and up to 80 % reduction in concentration of suspended solids [87] in the US.. These effects are also apparent in Yanweizhou Park (Wuhan, China), with a 70 %

runoff reduction, and in Scotland, where suspended solid concentrations were reduced to below 3 mg/L [87]. During intense rainfall events, infiltration rates of macro-pervious pavement reduce the effects of downstream flooding by 30 % [86], and are capable of withstanding up to 5 cm of rainfall [87], making permeable materials a highly efficient strategy for increasing water infiltration.

6. Sport: a positive driver for change?

The unifying power of sport has the potential to drive positive environmental change. For example, hosting large sporting events such as the Olympics and Paralympics, or the Football World Cup can act as an impetus for governments to enact ‘green’ initiatives. Countries bidding for large sporting events must now include clean energy provision and environmental metrics in their competition licensing criteria. The Seine cleanup proposal informed part of the winning bid for Paris to host the 2024 Olympics and has resulted in a 90 % reduction in volume of untreated wastewater released into the river [83]. Similarly, as part of the 2022 FIFA World Cup, Qatar inaugurated its first solar power plant, an 800-megawatt photovoltaic power station capable of providing 1.8 billion kilowatt-hours of clean energy per year [88], reducing CO_2 emissions by 26 million tonnes over its lifetime [89]. Finally, the Glasgow Indoor World Athletics Championships in 2024 became the first event to receive platinum level recognition for sustainability through their social impact partnerships including use of public transport, plant-based food sources, and redistributing excess food to local food banks [90].

On an individual level, athletes have considerable influence in the modern world and can leverage partnerships and sponsorships to align with sustainable organisations, promoting environmentally friendly companies. The Tour de France team *Team Total Energies* promotes a “strong ambition to become the company of all energies, committed to carbon neutrality by 2050”, and sustainable development goals [91]. The Tour de France generates 40 % of its revenue from advertisements and sponsorship and 55 % from television rights, and a cycling team is worth an average of $88.4 m in media exposure [92]. Therefore, by aligning themselves with environmentally conscious companies, athletes and sports teams can promote positive environmental change and increase revenue for companies working towards mitigating the effects of climate change.

Fig. 2 summarises strategies to reduce carbon emissions and increase physical activity through strategic urban planning. Fig. 2 also highlights current recommendations to attenuate heat stress in athletes and how sport may be a positive driver for environmental change at both an organisational and individual level.

7. Conclusions

In summary, increased urbanisation, air and water pollution and global warming will have immediate primary and secondary effects on global CVD morbidity and mortality. Importantly, the opportunity for PA, a potent and well-established preventative measure against CVD will diminish as climate change progresses. Future research should focus on the chronic effects of exercising in areas of high PM or ambient heat and investigate strategies to circumvent the potential negative health effects of doing so.

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CRediT authorship contribution statement

Eloise J. Thompson: Writing – original draft. **Sarah E. Alexander:** Writing – original draft. **Kegan Moneghetti:** Writing – review & editing. **Erin J. Howden:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare no conflict of interest.

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