

Physiology and climate change

Showcasing the work of physiologists across the world in a global effort to understand and find solutions for the effects of climate change

The Physiological Society

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FOREWORD

Climate change, environmental damage and dwindling natural resources are significant and escalating problems which affect us all. The threat that climate change poses to the health of humans, other animals and plants cannot be ignored.

As noted by the World Health Organization[1] the overall health effects of a changing climate are overwhelmingly negative. Climate change affects many of the social and environmental determinants of health and hygiene. These evolving health risks include:

- **Temperature-related mortality and morbidity**
- **Air quality deterioration which exacerbates cardiovascular and respiratory disease**
- **Impacts of extreme events such as higher rainfall and rising sea levels which impact for example water-borne diseases such as cholera**
- **Food safety and nutrition**
- **Mental health and well-being**

Physiology is an essential part of the scientific response as it helps us understand the consequences of climate change on the human body. As the science of how the body works, physiology explains the impact of climate change on our health and productivity, and therefore the very future of our species.

COP26 is taking place in Glasgow in November. It will bring together countries from across the world in what many believe to be the world's best last chance to get runaway climate change under control.

The first goal of COP26 is to halve emissions over the next decade and reach net zero carbon emissions by the middle of the century to limit global temperature rises to 1.5°C. The world is currently way off track.

Physiologists are contributing to this effort through research in areas such as developing more environmentally friendly nutritious diets, or exploring effective ways to reduce our reliance on air conditioning, a cooling system, which releases toxic gases into the atmosphere.

The second goal of COP26 is to urgently adapt to protect communities and natural habitats. People across the world are already living with devastating extreme weather heightened by the changing climate. We have all seen the terrifying fires and floods raging across the world over the last few years.

Physiology is essential to finding solutions for people facing hotter temperatures, extreme weather, fires and floods.

For example, physiologists use their specific expertise to look at how humans respond and cope with extreme heat to develop proposals for physiological adaptation (or acclimatisation), behavioural, infrastructure, and technological adaptation which can also inform public health guidance.

The current climate crisis has already resulted in a mass-extinction of numerous species and is likely to get worse. Physiologists are vital for conservation efforts of wild populations to make sure that they have an environment that supports their survival.

COP26 is a critical summit for global climate action and is being described as the most significant climate event since the 2015 Paris Agreement. As we look to COP26, all of us will be willing world leaders to unite and act decisively to get strong commitments and alignment to cut carbon emissions and avoid the worst effects of climate change.

As Chief Executive of The Physiological Society, I am proud of all the work physiologists across the world are doing in this global effort. This short pamphlet captures just a snapshot of their research.

Dariel Burdass
Chief Executive, The Physiological Society

1. https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health

Introduction: Physiology at a time of **Climate Crisis**

Professor Hugh Montgomery & Professor Mike Tipton

Let's not fool ourselves, climate change poses an immediate and grave threat to the plants and animals of our planet, including humans. As we approach the next international "Conference of the Parties" in Glasgow in November (COP26), hope is tempered by the fact that nearly three decades of these international meetings and negotiations has made no difference at all to the continued rise in greenhouse gas emissions.[1]

The energy equivalent of many tens of billions of Hiroshima bombs has been trapped since 1990 alone[2], the bulk in our oceans. Global temperatures are rising, ice melting (summer Arctic sea ice volume fell by three quarters, or 12,723km[3], from 1979 to 2019[3], the Greenland ice sheet alone loses >1 billion litres of meltwater/minute[4]) and sea levels are rising (by nearly 4.5 cm in only 16 years[5]). Extreme weather events are becoming ever more frequent: in June 2021, temperatures in Arctic Verkhojansk breached 48°C[6] and approached 50°C in Canada.[7] The world, and more areas of it, now sees twice as many days over 50°C as it did in the 1980s, with the increase being "100 % due to burning fossil fuels"[8]. Floods, droughts and storms are ever more frequent and severe.

Our current emissions trajectory will take us to the equivalent of atmospheric CO_2 concentrations of 1200 ppm and a temperature rise of about 5.5°C by the end of the century.[9] But it may be worse than that, as positive feedbacks amplify energy gain. With snow and ice melt meaning less reflection of shortwave radiation back into space, Earth's energy imbalance has doubled in only 14 years.[10] Arctic tundra melt is releasing methane, more than 80x as powerful a greenhouse gas as CO_2 in its first two decades[11], and is also ablaze releasing more CO_2[12]. In 2021, the Amazon became a net *emitter* of CO_2. Carbonate rocks are now warming and releasing methane[13]. And reductions in sulphates as we stop burning coal (which we must) will, in the short term, double atmospheric energy gain in only 25 years. The responses to such warming are also non-linear: recent Antarctic heating (at three times the global rate) threatens "*everything we value that sustains us*".[14] Sea level rise of tens of metres is possible in short timeframes and CO_2 concentrations now match those 3.6 million years ago, when sea levels were about 24 m higher than now.[15,16]

Limiting global temperature rise to a further 25% of that already seen (to 1.5°C) is, of course, nowhere near safe given that the changes we already experience will only worsen. But even this now requires not only rapid cessation of all emissions, but massive draw-down of CO_2 from our atmosphere. Even then, "climate changes would continue in their current direction for (up to) millennia" and it could take "millennia… for global mean sea level to reverse course."[17]

All plants and animals depend upon a stable and narrow range of environmental conditions to thrive and survive. By changing background "stable" temperature and water availability, such survival is threatened: over the next 50 years, "1 to 3 billion people are projected to be left outside the climate conditions that have served humanity well over the past 6,000 years, and without action, a substantial part of humanity will be exposed to mean annual temperatures warmer than nearly anywhere today"[18]. Rising seas and extreme weather events further threaten viability.

It is time for us all not just to raise the alarm but to act. Whilst enormous problems require enormous responses, such responses can come about by the accumulation of many individual acts – in our personal, professional and political lives.

The scale of the climate change problem is so vast that every scientific discipline needs to consider what it can do to help prevent a catastrophe. The articles within this pamphlet highlight some of the work physiologists are engaged in to respond to the climate crisis. In some cases this involves detailing its impact on different species. Others are measuring the impact of an aspect of climate change on humans and animals and trying to mitigate these changes to save lives.

It is clear that physiology, physiologists and The Physiological Society all have an important role to play in tackling climate change, from the micro to the macro level.

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See Appendix which has suggested actions from Professor Hugh Montgomery & Professor Mike Tipton for individuals on a personal, professional and political level.

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Photo credit: University of Sydney

Using physiology to tackle health problems resulting from heat extremes

Interview with Professor George Havenith & Professor Ollie Jay

Physiology is at the heart of a multi-disciplinary approach to understanding, and finding solutions for the impacts, of the health problems resulting from hot weather and heat extremes caused by climate change.

Professor George Havenith (University of Loughborough, UK) and Professor Ollie Jay (University of Sydney, Australia) met with The Physiological Society's Head of Policy and Communications, Andrew Mackenzie, to discuss the importance of their physiology research in tackling the impact of climate change.

Andrew Mackenzie (AM): Could you explain what you are trying to find out and why it matters to climate change policy makers?

Ollie Jay (OJ): We are taking a multi-disciplinary approach to understanding, and finding solutions for the impacts, of the health problems caused by hot weather and heat extremes.

The risk starts even before birth during pregnancy, when we know that extreme heat exposure can increase the risk of negative birth outcomes. We do other work that covers a range of contexts across the human lifespan, such as occupational and sporting settings, as well as the most vulnerable during extreme heat events such as the elderly, and people with cardiovascular disease. The reason we feel that all of this is important is that to date, in most of the approaches that have been taken, particularly from people in epidemiology and public health, describe what the problem is but there seems to be quite limited information on what the underlying mechanisms of the problem are. From a physiological perspective, we try to understand that so we can develop the most effective and comprehensive solutions.

George Havenith (GH): We've been looking for years and years at people exposed to extreme climates. We've been focusing on people overheating with very high core temperatures, such as athletes in hot countries or military personnel exposed to extreme heat during exercises.

However, it's become very apparent in the last 5 to 10 years that due to climate change, more and more people in countries around the world are becoming exposed to similar extreme conditions and are at increasing risk.

AM: Why do physiologists play an important role in the fight against climate change?

OJ: Many of the actions that are recommended by public health organisations seem to be based on conventional wisdom. Thermal physiologists can use their specific expertise on how humans respond and cope with extreme heat to better inform public health guidance. If information is not available then they can also perform studies that simulate the types of extreme conditions people are exposed to and measure how different interventions/actions influence the physiological strain that develops during heat exposure that ultimately leads to negative health outcomes.

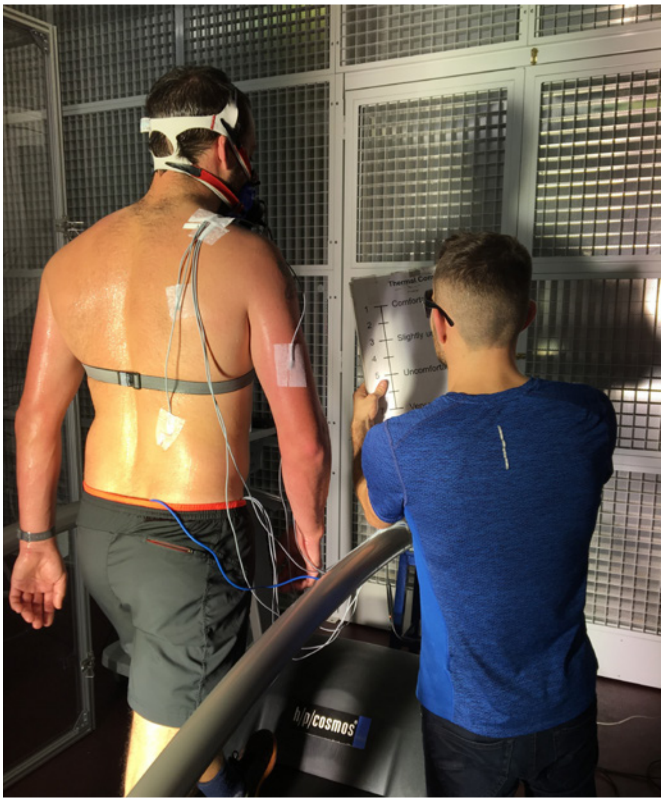

Photo credit: Loughborough University

As climate change results in more extreme weather, we need to think about how we can live in different regions as well as just survive in them. For a region to be truly inhabitable it means being able to work in these environments. It means pregnant women being able to give birth to healthy babies. That's why it's really important to think about it across the whole lifespan.

AM: Why are more frequent heat extremes due to climate change a problem?

GH: The frequency of extreme temperatures and the shift in the overall weather patterns throughout the year as a result of climate change means there will be more days that are hot. There will be more sequential days that are hot, and there will be more nights that are hot in between those hot days. From heat-related mortality and morbidity research we know that prolonged high temperatures and especially the lack of night-time recovery due to high night temperatures have a big impact on risk to life and health. There are lots of physiological issues related to this that are really going to play out much more due to climate change.

AM: What happens in the body when someone is exposed to extreme heat?

OJ: In the heat-related mortality and morbidity data, the three things you usually see are heat stroke, cardiovascular disease, and kidney disease.

Heat stroke is critical overheating, that is a very high internal body temperature, also coupled with your gut basically starting to leak. These endotoxins then set off a cascade of events. You have something called systemic inflammatory response syndrome, which then leads to widespread clotting and ultimately multiple organ failure and eventually death.

In heat-waves one of the most at-risk subgroups is people with cardiovascular disease. From a physiological perspective, we know that one of the first responses to heat exposure is that we have vasodilation, where we're redirecting blood away from the body core towards the skin surface. This is to support skin surface heat loss, but in order to maintain central blood pressure we must increase cardiac output – mainly through increasing heart rate. If there is an underlying infirmity because of cardiovascular disease, you may not be able to deliver enough oxygen to the muscle cells of the heart, which leads to a greater risk of a catastrophic cardiovascular event.

Finally, there is progressive dehydration. If those lost body fluids are not replenished over a prolonged period of time, that can lead to progressive dehydration that can exacerbate the cardiovascular issue. It can worsen body heating, and also lead to increased renal strain. You're asking your kidneys to work harder. Again, if you have an underlying kidney disease, then that becomes a problem.

AM: Why isn't the answer just to fit air-conditioning units in homes across the world?

OJ: The problem with air conditioning is that it's expensive to install and it's expensive to run. We have an inequality gap in society and climate change-related heat extremes are widening that gap. Some people think it's completely fine because they can turn their air conditioning on, but the people suffering the most, the people who will be hospitalised or die, typically don't have access to mechanical cooling. Across the world, it is often the people who are suffering the most that are contributing the least to the problem in the first place.

One of the other challenges with air conditioning is that it's environmentally unsustainable. If everybody turns to air conditioning for their cooling needs, then the associated increase in greenhouse gas emissions from the units themselves and as a function of the generation of electricity that is used to run them could have quite substantial negative effects on our climate in the future. As the world continues to warm, we need to find more sustainable ways to keep cool.

AM: So how do we protect people from these more extreme temperatures?

GH: We are part of this big EU-funded project, called Heat Shield, which is focusing on the impact of climate change on workers, in different industries like agriculture, tourism, construction, etc. Simple advice on how to better cope with those conditions would be to consider the pacing of work in addition to different ways of cooling. However, in a lot of countries workers don't have the choice to slow down. If workers can't pace themselves, their bodies will be pushed to more extreme body temperatures and cardiovascular loads.

Photo credit: Loughborough University

OJ: Right now, most solutions focus on cooling the environment that surrounds a person, which is quite an inefficient and energy-intensive process. However, the health problems essentially arise from the person getting hot, so if there are much more sustainable ways of cooling a person without cooling the air then these should be embraced. For example, we can accelerate body cooling via convection and evaporation if we move air more across the skin – this would require us to chill it less to get the same net cooling effect. Using water in a smart way is also a potential solution for some settings, especially those without electricity (e.g. during a blackout). Applying water to the skin and allowing it to evaporate has been shown in climate chamber studies to be an effective way of keeping physiological heat strain in check during simulated extreme heat events.

GH: Translating our physiological knowledge into sustainable design features is important. One of the industries we looked at in the Heat Shield project was transport. We looked at how you could design the cabins of a truck to get less impact of solar radiation, i.e. how you can reduce the cooling power required through design.

In many countries the buildings have very little insulation and very little building mass, which means they heat up very quickly. Depending on which climate area you're in, you'll have to take different measures to optimise the building. In general – you want to avoid the building heating up very quickly, purely by solar influx, which is what happens in most places. Unfortunately, people with low incomes, with the worst health status and the least health support, are usually living in the worst housing that heats up quickest.

AM: What can the individual person do?

GH: The most powerful cooling mechanism that humans have is sweat and sweat evaporation. The obvious one to look at is how you can optimise that sweat and sweat evaporation.

Even above 35°C fans still can be effective if you can stimulate sweat evaporation. Even though you push a bit hotter air over the skin, the sweat cooling is so powerful that if you can enhance that sweat evaporation, that will give you a big benefit up to quite high temperatures.

Ollie and his group worked through different heatwave scenarios and actually found that indeed for most heat-wave scenarios that have happened in the past, the fans would be a positive thing.

However, the use of fans is a really good example where the physiological research is crucial to ensure the advice provided is correct. We know that people start to sweat less as they get older, and that's where we therefore need to be more careful in using fans to enhance sweat evaporation. Once you evaporate all the sweat you produce, putting the fan on them is not helpful anymore, and in very hot, dry environments, for example, can become detrimental.

AM: What groups are most vulnerable to extreme heat caused by climate change?

OJ: The best way to probably think about vulnerability is as a continuum with physiological adaptive capacity/vulnerability, and then behavioural adaptive capacity/vulnerability.

From a physiological perspective, ageing is important. One of the main ways in which we keep cool is by sweating and the evaporation of that sweat. We know that older people are less able to sweat, which is a reason why we see older individuals being at a much greater risk during extreme heat events. Co-morbidities, or people with cardiovascular disease or kidney disease also exacerbate the physiological risk as well.

Physiological capacity often comes together with behavioural capacity. If you have reduced behavioural adaptive capacity because you're living in a poorly constructed house, or live in a hot country but can't afford an air conditioner, you are at greater risk.

People who live alone are also at a much greater risk. It's not loneliness that's killing them per se, but it's the fact that if you're not mobile, you live on the top floor of an apartment block and you're physiologically vulnerable to the heat, then you're in a really tricky position because your ability to extract yourself from that situation is really compromised.

AM: What should the public policy response be?

GH: Building design across the world is really important. If you look at big modern office buildings with lots of glazing, that's a big issue in terms of sustainable environmental design. There is a lot that can be achieved in the built environment. If you don't have any trees in your area, that will raise the temperature in the streets. Some cities are experimenting with different road surfaces or certain more reflective surface colours of the roads.

If you have green roofs, that will give you a much better climate in the city, and mixing different spaces, e.g. blue (water) and green (vegetation) spaces into the city landscape tends to have a positive impact on temperature in extreme heat environments.

OJ: You have the landscape level, the built environment level then the individual level. There are things you can do at each of these levels that can ultimately contribute to reducing the physiological heat strain, which is potentially harmful to a person. The issue with interventions at the landscape level and the built environment level is that they're essentially slow burners. If a heat-wave comes tomorrow, you can't just go out and plant a bunch of trees. For immediate resilience, we need to make sure that we're telling people to do the right thing at the individual scale.

Then for longer-term resilience we need to get the built environment and landscape levels right. These take time, but we need to start doing them now.

AM: Why should physiologists be around the table at climate change meetings like COP26?

GH: Successfully tackling climate change and its consequences is about the animals and the humans in the environment. If you don't understand what's happening with the physiology in the heat, it is very difficult to come up with effective solutions.

OJ: If you want to find the solutions that really work, then you need to understand how the subject matter works, right? If you're concerned about the person, but don't bother to actually understand how the person works and what's happening inside that body, then it would be like trying to fix a car without understanding how an engine works and who would do that?

AM: If you could be sat in front of all the different prime ministers and presidents at COP26 what would be the thing that you would ask them to do?

GH: Take appropriate and sufficient action now.

OJ: One thing I would say is really incentivising truly multidisciplinary research and action in this area. Disciplines exist in their silos and there's relatively little crosstalk among these silos. What we found is you've got epidemiologists and public health people working on heat and health, yet they often have a limited understanding of how humans physiologically respond to the heat. That is OK, because we can help!

When climate scientists are trying to predict areas of the world that will be uninhabitable in the future based on different projections of carbon emissions and the climate change that will follow that, they need to factor in physiology because there are so many differences in the physiological capacity that occur across the lifespan.

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Using medical technology to fight species extinctions

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Dr Barbara G. Shinn-Cunningham & Dr Alexander Ruesch

Physio-logging uses non-invasive sensing technology to continuously measure physiological function in different species, and will be vital in the fight to save species from extinction caused by climate change.

The current climate crisis has already resulted in a mass-extinction of numerous species. Without immediate action, this crisis will only worsen. Eco-physiology can play a key role in species conservation as it will give insight into physiological limits of survival. Understanding such limits is crucial when working to create conditions that ensure species will survive. There are few long-term projects that help identify baseline physiological function, yet such studies are vital to understanding the basic needs of species and identifying how changes in the environment alter animal health and function. For example, marine mammals obtain their food underwater, but must return to the surface to breathe. Thus, while diving on a single breath of air, they have limited time available for underwater excursions. If food resources decline, forcing them to spend more time foraging and reducing their foraging efficiency, their probability of surviving and reproducing will decrease. In addition, increasing water temperature, ocean noise and pollution may also significantly alter their life circumstances.

Increasing water temperature may affect thermoregulation, exercise capacity, and metabolic rate, in addition to prey distribution and availability. Noise pollution may not only directly cause hearing damage, but also can prompt behaviours to avoid the sound source, which will reduce the time available for foraging and increase metabolic cost from swimming. Pollution, such as oil, and eutrophication resulting in harmful algal blooms (HABs) may have harmful effects on the skin, lungs and brain.

Our physiological knowledge of wild animals is limited; most studies have examined captive or restrained animals, whose physiology may not reflect that of wild animals. Future miniaturisation of electronic sensing technology may provide a means to measure physiology in free-ranging animals, which will revolutionise our understanding of physiological function of wild species. For example, heart rate has been difficult to measure due to motion artefacts, especially in sea water, where it is nearly impossible to obtain a noise-free signal.

Recently, a new device has been tested in freely diving seals and breath-hold diving humans that uses light emitted from light emitting diodes (LEDs) in contact with the skin, commonly called near infrared spectroscopy (NIRS). Because the optical characteristics of tissues and blood differ, NIRS can be used to estimate blood volume changes and measure arterial blood oxygen saturation (from 0%-100%), as well as changes in tissue saturation with oxygenated blood.

You may have had a similar device, commonly called a pulse oximeter, placed on your finger at your doctor's surgery in order to measure your pulse and arterial oxygen saturation. To measure and identify tissue and blood oxygenation, NIRS takes advantage of the different colour the blood acquires when it exchanges carbon dioxide (darkish red to blue) for oxygen (brighter red) inside the lungs. The colour of the blood changes because the haemoglobin inside the red blood cells favours the absorption of a different range of light wavelength (colour). This predictable colour change can be measured by shining two different light colours in the red and near-infrared range of the light spectrum into the body.

The two wavelengths of light are absorbed differently, depending on the amounts of oxygenated and deoxygenated haemoglobin. Because a portion of the light is scattered back into a photo detector (see Fig.1B), we can measure the change in light intensities and calculate the underlying change in haemoglobin carrying or not carrying oxygen. As the heart pumps blood through the body, the blood volume and haemoglobin concentrations vary with every stroke of the heart (Fig.1C). These changes can give us vital information about heart rates and the changes in oxygen concentration in the blood. Note how oxygenated blood (red line in Fig.1C) pulsates stronger than non-oxygenated blood (blue). This is because only arteries, which are oxygen rich, pulsate in the body. This pulsation in arteries is what gives rise to the field and name of "pulse-oximetry".

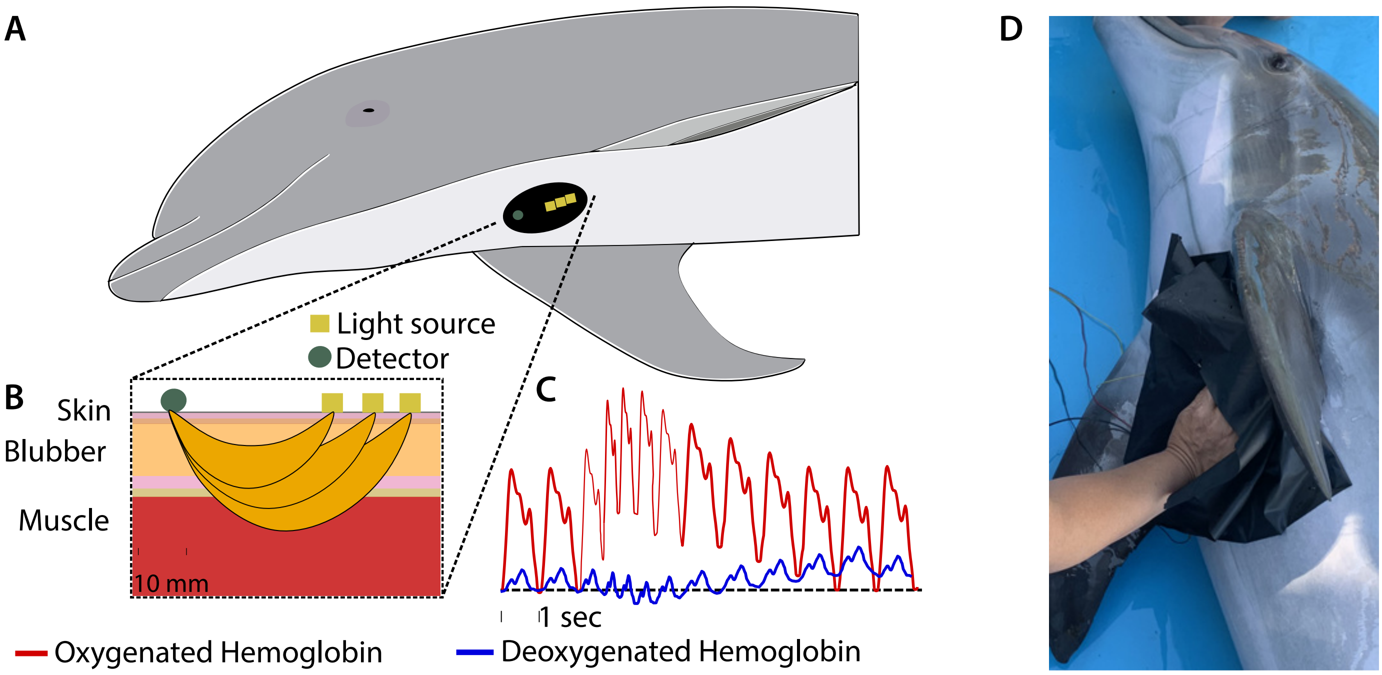

Figure 1: The theoretical application of NIRS (**A**) between the flippers is shown to probe muscular oxygenation in a common constellation of multiple light sources (each with 2 different coloured LEDs) and one detector. **B** shows a sensitivity map through tissue layers of the dolphin as a parabola shaped average photon path. In **C**, expected data are simulated for a respiration event with increased heart rate and oxygenated haemoglobin (red) and a decrease in deoxygenated haemoglobin (blue). A first test measurement on a voluntarily beached male bottlenose dolphin with a hand-held NIRS device is shown in **D**. The black cloth blocks sunlight from interfering with the optical signal. Photograph taken with permission at the Siegfried & Roy's Secret Garden and Dolphin Habitat, The Mirage, Las Vegas, NV, US.

Over the last 2 years, this tool has been developed to study physiology in dolphins (Fig.1D). Recent unpublished work has shown that this device is able to measure the oxygen content and heart rate from these marine mammals. Future goals include making the device waterproof for the field and testing it on free-swimming dolphins. Such a device will allow direct measurements of metabolic rate – and when used on free-swimming animals, it will be able to directly assess the energetic costs of different natural activities such as swimming and diving. Such a tool will enable scientists and conservationists to directly assess the physiological impacts that climate change, noise pollution and disturbance, and over-fishing have on dolphins and other species. Such information is vital for conservation efforts of wild populations to make sure that they have an environment that supports their survival.

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Killer heat – predicting heat-related mortality in desert wildlife

Professor Andrew McKechnie

Animals inhabiting the world's deserts are among the most vulnerable to climate change. Physiological studies reveal how the risk of heat-related mortality will increase greatly in coming decades, potentially driving large biodiversity losses in arid regions.

Increases in the frequency of extreme weather events – heat waves, droughts, fires, storms and floods – associated with climate change threaten natural systems across the planet. More frequent and intense heat waves, besides causing large numbers of human deaths, are also greatly increasing the risks of mortality among wild animals. In November 2018, for instance, Australia lost one third of its population of a large species of fruit bat – the spectacled flying fox – during two days of extreme heat in the Cairns area. Over 200 endangered Carnaby's Black-Cockatoos perished during a 3-day heat wave that struck southwestern Australia in January 2010; at some breeding sites 50% of adults died. Deaths on this scale can have serious consequences for animal populations, particularly those of range-restricted threatened species.

Historically, most heat-related mortality events have involved Australian birds or bats, but similar events are now starting to be reported in other regions. For example, November 2020 saw South Africa's first major heat-related mortality event when birds and fruit bats died on a single very hot day in northern KwaZulu-Natal province. Ongoing warming, exemplified by the unprecedented air temperatures approaching 50°C in southern Canada in late June 2021, raise the possibility of future mortality events occurring at much higher latitudes than they have in the past.

To predict where, when and how frequently these mortality events will occur under future climate scenarios, my students, collaborators and I study how animals regulate their body temperature during hot weather. Over the last decade, we have collected data on the capacity of arid-zone birds from Africa, Australia and North America to avoid lethal heat stress during extremely hot weather. Our work has revealed that species vary widely in their heat tolerance, with songbirds among the groups most vulnerable to mortality during severe heat waves. Groups like nightjars and pigeons and doves, on the other hand, have more efficient mechanisms for cooling and fare better at very high temperatures.

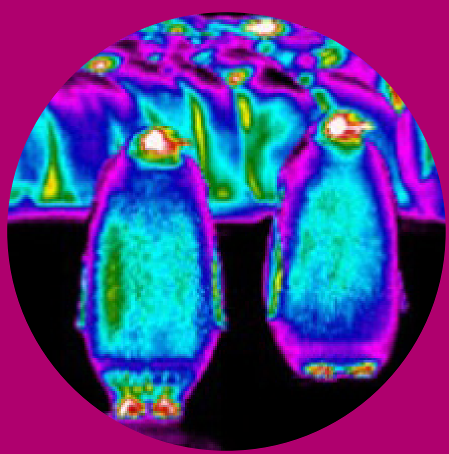
When combined with models of recent and future climate, our research on avian heat tolerance provides the basis for detailed models of how the risks of mortality events will escalate further in coming decades. In both the American southwest and the arid interior of Australia, the likelihood of mortality events each summer will increase dramatically. Under the United Nations "worst-case" emissions scenario (RCP 8.5), parts of Arizona where small desert birds experienced moderate risk of lethal dehydration on fewer than 10 days per summer between 1980 and 2012 will see these risks increasing to more than 50 days by the end of the 21st century. Similar changes will take place in Australia, with conditions in the far northwest of that continent becoming too hot for the persistence of many songbirds and parrots that are currently found there.

Earth's deserts are home to species exquisitely adapted to harsh conditions, some of which eke out an existence in even the most inhospitable dryland landscapes. But climate change is creating conditions under which even the hardiest of species will be unable to persist. Our research on both direct, lethal effects of hotter conditions and chronic, sublethal effects associated with birds being forced to spend longer periods resting in shade (and hence, less time foraging for themselves and their chicks) suggests arid regions will lose much of their biodiversity unless urgent action is taken to slow global heating. There are stark similarities in the consequences of more intense and frequent heat waves for wildlife and humans. For both, heat will become a significantly more dangerous natural killer and Earth's hottest regions may be rendered unhabitable by the end of the century. The impacts of extreme heat waves remind us, once again, that the well-being of humans is inextricably linked to that of the animals with which we share the planet.

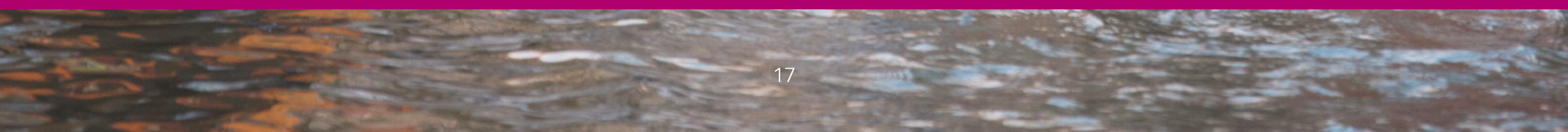
Professor Andrew McKechnie

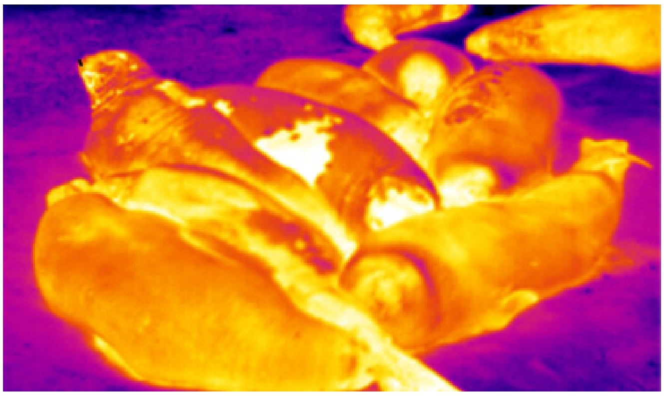
University of Pretoria and South African National Biodiversity Institute

Animal physiology in a changing climate



Dr Dominic McCafferty





Understanding how species are thermally adapted to their environment provides valuable insights into the ability of animals to tolerate rising temperatures and changes to their habitats as a consequence of climate change.

Birds and mammals in polar environments have evolved physiological and behavioural mechanisms to reduce heat loss in extreme low temperatures, but now face temperatures that are rising at three times the global average rate. These species may be unable to tolerate such warm conditions, and their survival may be challenged by the greater frequency of extreme weather events that climate change brings.

As thermal ecologists, we study the thermal physiology and behavioural thermoregulation of a range of seals and seabirds in Arctic and Antarctic environments. We use thermal imaging to measure the surface body temperature of these free ranging animals, allowing us to investigate how weather influences their ability to thermoregulate[1,2,3,4]. By modelling how these species may lose or gain heat from their environment we are able to estimate the energy cost of thermoregulation and how this responds to changes in environmental conditions[5].

This detailed understanding of thermal physiology provides us with the ability to predict effects of climate change on species that may focus conservation efforts in protecting polar habitats.

Animal physiologists may also contribute to the challenges of climate change mitigation through working closely with engineers to investigate bioinspired designs for the human built environment[6,7]. Through natural selection animals have evolved adaptations to all extremes of heat and cold. Endothermic species such as birds and mammals have the ability to minimise energy use and maintain thermal comfort. These insights from the natural world may therefore aid the design of insulation and temperature control to reduce energy use in buildings.

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Image Credits

Wandering Albatross: Carrie Gunn, BAS, UK

Emperor Penguins: André Ancel, CNRS, France

Southern Elephant Seals: Laureline Chaise ENVA, France

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Living in a future with climate change – challenges and opportunities for human thermal resilience

Dr Hannah Pallubinsky

As comfort seekers, we avoid being exposed to temperatures outside of our comfort zone. However, in the light of climate change and the need to drastically reduce our carbon footprint, we need to rethink many of our habits. Enhancing our own human resilience, by training our bodies' thermoregulatory system, presents an opportunity to reduce energy use, while at the same time improving our health.

As the warming of the Earth's climate continues, we must learn how to adapt to its impacts, while also acting to prevent their progression. In 2021 alone, we witnessed a variety of severe weather phenomena (such as the Western North American heat wave, the European floods, and wildfires across the globe) caused by or contributed to by climate change[1,2]. Even the most promising climate change projections, which are subject to the implementation of powerful emission-reduction policies and active removal of greenhouse gases from our atmosphere, foresee a further increase of global average temperature[3]. It is not necessarily this average temperature increase, but especially the concomitant thermal extremes, that are challenging and pose an acute risk for human health and well-being. Much scientific and political interest lies in making our cities and living spaces more resilient, by implementing new technologies as well as physical reinforcements, and by adopting innovation in urban planning. However, we should consider that not just our physical environment, but also our human bodies have the potential to become more resilient, for example in withstanding thermal challenges like heat waves and cold spells. Therefore, it is important to evaluate the current situation with respect to thermal environments we are exposed to in our daily lives, and to implement evidence-based strategies for improving "*thermoregulatory fitness*", while also mitigating the impact of climate change for human health and safety.

Ever since the existence of human life, the human body has needed to adapt to various thermal environments for survival. The natural thermal environment has always fluctuated – not only seasonally, but also in the course of day and night. Evolutionary processes, the plasticity of the human physiological system, and, importantly, behavioural adjustments, enabled the human species to adapt to a wide array of different climatic zones[4,5]. Leaping to the situation nowadays, it may, however, be more accurate to say that we manipulate the indoor thermal environment to our wishes and desires, rather than adapting to our former natural habitat – outdoors. Based on thermal comfort research published in the 1970s[6,7], thermal neutrality has been assumed to be the most comfortable and productivity-promoting environment for the majority of building occupants. Subsequently developed standards for indoor environments (e.g. ASHRAE-55[8]) supported the goal to strive for a *thermally neutral* environment in buildings. Consequently, in most developed and industrialised countries, people are hardly ever exposed to the variation of outdoor conditions anymore, as we spend the majority of time (~90%!) indoors[9].

The pursuit of omnipresent thermal comfort comes at a high cost: firstly, it is very expensive and energy-consuming: 30% of the primary energy supply is used for heating, ventilating and air-conditioning of commercial and public buildings[10]. Secondly, these days, we are used to uniform and thermally comfortable environments to such an extent that we have become vulnerable to large natural temperature fluctuations. Technological advances over the past century have allowed us to be independent from weather and season indoors. In fully air-conditioned buildings, indoor environmental standards prescribe that air temperature should minimally vary around the assumed comfort setpoint (often ~21°C) year-round. When people move from their air-conditioned houses to air-conditioned cars and air-conditioned work spaces, and vice versa, the opportunity for exposure to temperatures outside the comfort zone is minimal. We no longer "train" our thermoregulatory systems, and thereby omit any form of natural acclimatisation. The lack of "temperature training" reduces our thermoregulatory capacity to cope with temperatures outside of the comfort range, and thus decreases our resilience.

In the light of climate change, moving away from tightly controlled indoor thermal environments to allowing more variation (dependent on time of the day and season), offers several major advantages. Previous studies have shown that repeated exposure to temperatures outside the comfort zone induces physiological and perceptual acclimatisation processes, and widens the range of acceptable temperatures[11-14]. For example, it has been shown in both young healthy but also middle-aged and overweight individuals that acclimatisation to heat improves the body's ability to regulate its temperature, e.g. by means of enhanced heat loss via the skin and more efficient sweating[13,15]. When a heat wave occurs, especially people with pre-existing conditions, such as cardiovascular or metabolic disorders, are at risk due to impaired thermoregulatory capacity. Several studies demonstrate that acclimatisation to heat, and specifically so-called heat therapy, improves cardiovascular function and reduces cardiovascular strain during heat exposure, thus attenuating the risk of heat-related cardiovascular problems[13,14,16,17]. Furthermore, evidence exists that regular exposure to temperatures outside the comfort zone improves glucose metabolism and metabolic health[14,18,19].

Overall, there are many reasons to re-assess our habits of constantly seeking thermal comfort in our everyday lives and to start enhancing our thermoregulatory resilience. Seizing the opportunity of allowing more thermal variation in our everyday life can aid in adapting to climate change and improving cardiovascular and metabolic health at the same time. Furthermore, it has great potential to reduce energy use and save precious resources. Importantly, this does not ignore that we must protect ourselves, and especially vulnerable individuals, from the hazardous effects of thermal extremes: general recommendations to cope with heat waves and other weather events, e.g. avoiding direct sun radiation and ensuring sufficient hydration, are indispensable[20].

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Applied physiology: a critical discipline in times of climate change

Professor Mike Tipton, Dr Gemma Milligan & Adrian Mayhew

Climate change will affect all aspects of life, the species around us, where we can live, where and how we can travel, and what we can grow and therefore eat. Although the predicted increases in average daily temperatures are within those that most, but not all, humans can accommodate[1], the increasing energy level in the atmosphere is already changing weather patterns, creating more frequent and more extreme weather events: heat-waves, storm surges, droughts, cold snaps and hurricanes. Sea levels are rising and countries and communities disappearing, while deserts are expanding[2,3].

Worldwide, climate change is also driving more frequent and severe flooding events[4]. The UK is no different[5].

These changes have placed a demand on resources to improve flood defences, and on those required to perform search and rescue in flooded areas. With research into the physiological responses of flood rescuers, we are now beginning to understand the demands placed on rescuers, the need for customised personal protective equipment (PPE) and other kit, and the standard operating procedures (SOPs) and policies for those conducting rescue operations.

Our research in this area[6] was the first to focus on the physical and thermal demands placed on flood rescuers. Ten experienced flood rescuers undertook a 60 minute simulated flood rescue task in the coldest and warmest flood rescue conditions experienced in recent years. In the "cold" condition, participants stood in knee-height moving water (temperature 7.7°C, velocity 4.8 $km.h^{-1}$), with 4°C air temperature, 16 $km.h^{-1}$ wind speed, 80% relative humidity and simulated rain. In the "warm" condition, in line with SOPs at the time, participants were asked to walk at 2.16 $km.h^{-1}$ in water flowing at 4.8 $km.h^{-1}$. However, the first participant found this impossible and following 10 min of exercise was

exhausted and had a predicted time of 43 min to a deep body temperature of 40°C. This condition was then moderated to six 7 minute stages with 3 minutes rest between stages. Participants were again immersed to knee height and walked from one end of a swimming flume to the other (3.30 m) at a speed of 2.16 kmh^{-1}, in water flowing at 3.2 $km.h^{-1}$. Participants walked into the flow of water pulling a 10 kg load attached to a 1:1 pulley system. They then turned around and walked with the flow of water, controlling the release of the 10 kg; the load represented pulling a rescue boat. Air temperature, water temperature, humidity, wind speed and radiant heat load were 20°C, 15.6°C, 40%, 0 $km.h^{-1}$, and 500 Wm^{-2}, respectively.

The results were illuminating. In the cold, foot temperatures cooled to the region where non-freezing cold injury becomes a risk, and neuromuscular cooling reached a level where strength and agility were impaired. The first result in the "warm condition" indicated existing SOPs were not tenable. Even the less stressful "warm condition" resulted in the deep body temperature increasing uncontrollably in half of the participants. By the end of the warm exposure, average heart rates were 87% of predicted maximum, oxygen consumption averaged (SD) 30.62 (7.83) $mL.kg^{-1}.min^{-1}$ and average (SD) sweat loss was 1.06 (0.31) L. These values are too high for this to be a sustainable activity without mitigation (e.g. longer rest periods, hydration strategies, larger rescue teams, and bespoke PPE).

These findings have changed the SOPs of flood rescue organisations and the PPE offered to them[7]. As a result, flood rescuers should be safer and perform more effectively in flood rescue situations, to the benefit of all. This is yet another example of the importance of physiology research and its application for the health and safety of rescuers and the communities they serve. As always, however, prevention is better than cure. We must do all we can to mitigate future climate change, rather than just responding to the problems it causes, especially if that response puts rescuers at risk.

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Protein nutrition, healthy ageing and climate change: how do we combine the three?

Dr Oliver Witard

This article aims to present a thought provoking perspective on how dietary protein choices can impact both our muscle physiology and the natural environment. Muscle physiology is framed in the context of maintaining muscle size and function as we age. The environment refers to the climate change effort that we, as a collective society, must embrace.

Diet and greenhouse gas emissions

Food production accounts for 20–30% of the UK's greenhouse gas emissions (GHGE) and therefore plays an important role in climate change[1]. Whereas agriculture contributes directly to GHGE, particularly methane and nitrous oxide production, indirect contributors include transportation, energy supply, and waste management[2]. Greenhouse gases are emitted at every stage of the food chain, from agricultural production (farming methods and land use) through to processing and manufacturing (packaging and transportation), consumer activities (storage and cooking), and food waste disposal. Meat and, to a lesser extent, milk and dairy are the largest contributors to diet-related GHGE[3]: ruminants belch methane (more than 80x as powerful a greenhouse gas as is carbon dioxide in its first 20 years; and pasteurisation of milk, and refrigeration of dairy products and meat, are especially energy intensive). Further, rainforest destruction for growing animal feed, or for grazing, removes a major carbon sink. Accordingly, most of the focus on diet and the climate change effort has centred around reducing dietary intake of meat (primarily red meat and processed meat) and dairy. Such a change in dietary pattern will have a significant nutritional impact on patterns of dietary protein intake given that more than 60% of protein consumed in the UK is derived from animal proteins, of which meat and dairy make significant contributions[4].

Protein and ageing muscles

The biological ageing process is associated with a gradual loss of skeletal muscle mass and function, collectively termed sarcopenia. Muscle loss typically begins during the 4th/5th decade of life at a rate of 1% per year until 70 years, increasing to 1.5% per year from 80 years onwards. Once a critical level of muscle loss is reached, detrimental health consequences include reduced mobility, a loss of independence, and increased risk of falls.

Skeletal muscle is comprised of muscle proteins that are continuously remodelled. A key metabolic process of muscle remodelling is muscle protein synthesis (MPS) whereby amino acids are incorporated into new functional muscle proteins. The MPS response to food and/or exercise is impaired in older adults; a concept coined "anabolic resistance". To overcome anabolic resistance, dietary choices should consider the most anabolic protein sources. A combination of factors determines the anabolic potential of a protein source. First, the digestibility of the protein source determines the bioavailability of amino acids as substrate for the synthesis of new muscle protein. Second, the protein source must constitute a complete profile of all nine essential amino acids (EAA), of which a high leucine content is necessary for maximal stimulation of MPS.

Characteristic differences in EAA profile and leucine content exist between plant- and animal-based protein sources[5]. The total EAA content of animal proteins typically exceeds plant proteins. Plus, animal-based protein sources typically boast a complete EAA profile, whereas most plant proteins are deficient in one or more EAA, usually lysine or methionine. The leucine content of animal proteins is typically greater than that of plant proteins.

Several studies have compared the capacity for plant and animal proteins to stimulate MPS, A seminal study by Wilkinson and colleagues recruited trained young men who consumed either fluid skimmed milk or a soy protein beverage immediately following exercise[6]. Both drinks contained 18 grams of protein. Milk protein was shown to stimulate a 34% greater MPS response than soy protein. This outcome was attributed to the greater digestibility, superior EAA profile and higher leucine content of milk.

Two other studies in older adults demonstrate that ingesting a 4 oz (113 g) steak stimulated a greater MPS response compared with a soy-based beef replacement, whereas casein protein (the main milk protein) stimulated a greater MPS response than wheat protein[7]. Based on these scientific studies, a general consensus has been reached that animal proteins, in particular dairy proteins, are more potent in stimulating MPS compared with plant proteins. However, this statement is limited to the comparison of dairy proteins with soy and wheat only.

Why study alternative plant-based protein sources?

Plant-based protein-rich foods may be considered more sustainable for the environment than animal-based protein-rich foods. Based on estimates of GHGE associated with the UK's supply and production of different food groups, plant-based food sources fall into low and moderate carbon footprint categories, whereas animal proteins fall into the high category[2]. So, where next for future study into the anabolic properties of plant-based proteins?

Combinations of potato and rice protein, corn and pea protein, and soy and hemp protein appear to be complementary in providing a complete EAA profile for supporting MPS. In practical terms, a bean and quinoa bowl provides an example meal to "cover" amino acid requirements from a single vegetarian dish. At the risk of opening up a can of worms, a similar gap in knowledge exists for insect-based sources of protein. Based on amino acid profile, beetles, mealworms, ants and termites are promising sources.

How do we tailor protein recommendations for muscle health and the environment?

Moving forward, a multidisciplinary approach is required where we combine our knowledge of nutrition and physiology, with a mathematical modelling approach. A study by Macdiarmid and colleagues modelled the dietary changes required to achieve nutritional requirements for health while meeting target reductions in GHGE derived from dietary means[8]. Findings revealed that a balanced, rather than extreme approach, is possible, i.e. a sustainable and healthy diet can be achieved without completely eliminating meat and dairy from the UK diet.

Take-home messages

Diet clearly makes significant contributions to global warming and climate change. Regarding protein nutrition, the anabolic potential of a protein source is dictated by three key factors, namely the digestibility of the protein, the EAA profile and the leucine content. On the basis of current scientific knowledge, animal-based protein sources are more anabolic than plant-based protein sources, at least on a dose-matched basis. Future protein recommendations should take a holistic approach by considering muscle health, appetite and other nutrients of concern. But climate change threatens our very survival and that of our ecosystems and consideration of this fact must drive food policy above all else. These recommendations will likely include a marked increase in plant-based foods, but without elimination of meat or dairy.

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Appendix:
Actions individuals can take

Professor Hugh Montgomery & Professor Mike Tipton

It is time for us all not just to raise the alarm but to act. Whilst enormous problems require enormous responses, such responses can come about by the accumulation of many individual acts.

Here are suggested actions that **Professor Hugh Montgomery** & **Professor Mike Tipton** suggest individuals can take in their personal, professional and political lives:

At a personal level you can:

- **Measure your carbon footprint.** NB. 1 Tonne CO_2 is 1000 kg, or about 520,000 litres. You need to be aiming for zero. It's really hard. So act at once on the big ticket items (pre-Covid flying, for instance), then chip away at the other items. Redo your calculations every 6 months or so, and chart them to ensure that you ARE making progress. More info: www.carbonfootprint.com/calculator.aspx

- **Home power supply.** If you haven't already, move to a 100% renewable electricity supplier. For many reasons, much of what is on the market as a "green tariff" is not going to make a difference. Check out – www.goodenergy.co.uk or www.ecotricity.co.uk. Make the switch now, while you are thinking about it.

- **Install solar PV cells.** These are now inexpensive – you make your own electricity and get paid for it: www.ofgem.gov.uk/publications/feed-tariff-fit-tariff-table-1-april-2021. The value of your property is also enhanced or maintained.

- **Insulation.** Home insulation makes a BIG difference to energy loss: external (or internal) wall insulation, secondary or double glazing and loft insulation. There are grants available, too: www.gov.uk/guidance/apply-for-the-green-homes-grant-scheme

- **Turn the heating down.** Every degree reduction saves 7-11% of your emissions, and your costs. Remember, 16°C is still a warm spring day equivalent. Just add a jumper if slightly chilly.

- **Transport.** If you have to travel, then this order is preferable: walk or cycle; use mass public transport (bus or train); car-share.

- **Food.** Ruminants belch methane which is more than 80x as powerful a greenhouse gas than CO_2 in its first 20 years so cut down (or stop) eating red meat, and reduce dairy consumption (consider substitutes such as oat milk). Eat a diet based on local, seasonal vegetables: this reduces air miles, and the massive cost of refrigeration (an off-season apple has a massive carbon footprint, as it has either been flown in from Argentina or Spain or has been kept refrigerated).

- Offset. This is NOT the solution to reducing emissions. It is what must be done to absorb the emissions that you have not been able to avoid. Make your changes, then recalculate your carbon footprint. Buy trees to absorb those emissions. At maturity, a tree will draw down 21kg CO_2 per year – that's 50 trees per tonne. There is a degree of unrealistic pricing out there; so if an organisation says they can grow, plant and tend a sapling for £5.00, be very suspicious. Consider Heart of England Forest: www.heartofenglandforest.org/donate/dedicate-tree. At £17.00 per tree, you will need to find £850 per tonne to offset. In fact, this is an underestimate, as this is absorption at maturity. The cheapest option is thus to lower your carbon footprint.

- Spending. If you have an ISA or a pension, move it away from any investment in fossil fuel extraction, and seek a "green" fund. Consider which businesses you reward with your trade. What is their environmental footprint?

- Engage others to act. Evidence shows that a trusted friend has the greatest impact on behaviours. Who likes/loves and trusts you? – Talk to them. Get them to act.

At a professional level:

- Your work. Ask those that want you to help them (give presentations etc.) if they have policies in place to deal with climate change. Make this a prerequisite of your assistance.

- Your employer. Talk to your employer e.g. a university. A good place to start is often the Estates Manager. Is there a Sustainability Officer? Find out what they've done and what they COULD do with a mandate/support from above. Then engage the Provost/Deans/Council etc. Engage your students. Work with them all to deliver all the "personal" changes listed above.

- Procurement. This is a BIG item, which can drive huge change. Where you have control, act, or where you don't, ask your university or employer to act. Write into all procurement contracts that the first ranking item will be environmental footprint. Make this clear in advance. Suppliers will change.

At a political level:

- Join others according to your taste: Greenpeace, Friends of the Earth or others. Contact your MP (and prospective candidates from other parties) and make sure that they understand that you will vote on aggressive change to save our environment, and us.

The Physiological Society

As the largest network of physiologists in Europe, with academic journals of global reach, The Physiological Society continues a 145 year tradition of being at the forefront of the life sciences. We support the advancement of physiology by promoting collaboration between physiologists around the world, organising world-class conferences and publishing the latest developments in our scientific journals. Research in physiology helps us to understand how the body works in health, what goes wrong in disease, and how the body responds to the challenges of everyday life.

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