# Climate change and agriculture:

# adaptation and mitigation[1]

**Tim Benton**

Let's begin with some definitional stuff. The food system is the entirety of the production, processing, transport, consumption, retailing of food including its impacts on nutrition health and well-being. And as you can see from this cartoon production of food impacts on a range of different environments on the left-hand side, goes into some sort of supply chain in richer parts of the world - the blue - and then ends up in a retail outlet or some market where we choose the food that we want to consume and it impacts on our nutrition health and well-being and at various places waste comes off. And of course our wellbeing is impacted, by the environments in which we live. So the reason for taking a food system approach is really that we have spent on a global basis the last 70 years designing a food system and almost every country in the world - their food that they might consume is some combination of local production and global trade and the food system includes the environments and the impacts in broader sense than just agriculture. So by taking a food systems lens it allows you to kind of draw the focus on where I think it should be, which is ultimately the food system is there to improve our health and well-being. And so there's a lot of kind of current focus on our health and well-being and designing the food system better to deliver that as I will explain as we go through.

Now moving on and just starting with changing climate change and climate change is clearly not rocket science in the sense that most people would have encountered this in school when learning about the greenhouse effect and climate change works exactly analogous to the way a greenhouse works. So you have shorter wavelength radiation coming through from the sun goes through the glass in a greenhouse hits the ground, warms up the ground and the ground then emits infrared radiation which is longer wavelength radiation and that gets trapped inside the greenhouse by the glass. It doesn't get through the glass. And so it warms up. And in an exactly analogous way greenhouse gases create a equivalent to their greenhouse class around (through the) through the atmosphere. And we can say it's not rocket science here is a picture from a paper in 1938 where the figures are drawn by hand but the climate scientist, a chap called Guy Calendar, showed for that time period that the CO2 concentration was rising and was responsible for a chunk of global warming. So that was 80 odd years ago. We have known for that sort of length of time.

And then the greenhouse gases that create the greenhouse effect, the kind of equivalent of the layer of glass, are primarily, the one that's most focused on is carbon dioxide and the top figure shows the growth in carbon dioxide effectively at my lifetime. And as you can see it's a curve that's accelerating, it's a curve not decelerating. And the bottom graph, is a kind of quite frightening graph because it shows the greenhouse gases over the last 800,000 years and the red dot is where we are as of September 25th 2019, parts per million of 409, considerably greater than time in human history, since we evolved effectively. Greenhouse gases are not just a limited to carbon dioxide, of course. Methane

[1] Minor corrections, eg removing repetitions, hesitations, correcting mis-spoken words in the audio have been made to this transcript.

and nitrous oxide are the other 2 main families of greenhouse gases and part of the interest in this space from an perspective of courses is that carbon dioxide is liberated when we chop down trees to bring land to agriculture. Methane comes from rice production and from ruminant digestion and nitrous oxide comes from soil or management and manure, management and synthetic fertilisers. So actually methane and nitrous oxide are very closely associated with agricultural production.

### *Climate change: what does it mean?*

So climate change, what does it mean? Often people think of climate change purely in terms of a gradual increase in global temperature. And this figure, the one on the top, shows that gradual increase in global temperature over the last 100 or so years. And as you can see from about 1900 the temperature on average has been going up and the colour codes in the top graph are the 20 hottest years in red in the 20 coldest years in blue, and as you can see that the hottest years are the most recent years and coldest ones are the longest away. Very clear trend. The stripy diagram below is something that has recently gone quite viral because it's another pictorial representation more or less of the same data. Where it is red it's hotter than average where it is blue it is colder than average and each vertical stripe is year dating back to 1850 to 2018. And you don't have to be a statistician to point out that the red is at one end as the world is warming. So clearly climate change is partly about global warming but it is also increasingly, from a human perspective, we're recognising that climate change is about not just the changing climate but the changing weather.

And here are a set of pictures of some of the things that are increasingly obvious from our perspective. So there's super typhoon Corfu, and hurricane Patricia in the same week in 2015, the biggest storms in both hemispheres in the same week. A picture of the bottom is a dried out dam in Californian 10 year drought. And in 2019 and in 2017 we've had very extreme heat events and we've effectively got one degree of global warming. The tweet on the bottom shows that under a one degree of global warming average increase when it gets hot it can be 10° hotter than it should be. The picture of the 18th-century bridge in Tadcaster in the UK - just this to make a point - the climate is warming weather is becoming more extreme, rainfall is becoming more extreme, flood events are becoming more extreme and so that bridge that has been a couple hundred years washed away under extreme flooding. And then of course we have droughts, we have extreme heat waves, we have extreme winds, extreme everything. So the extreme weather is that an additional thing about climate change that we really are only starting to get our head around. And one of the interesting things as the extreme weather on a global basis is often interconnected by the way that the Jetstream in the upper atmosphere works. And this is an example of a map from 2012 and what you can see on the left-hand side over the United States red and there was a drought which affected maize yields in the breadbasket in the Midwest. In the UK and over that portion of north-west Europe, you can see blue colours, we had an extremely wet year, no sunlight at all. Yields were affected because of waterlogged ground and low light intensity. And then if you move towards Eastern Europe getting the red again we have a drought that affected grain yields in Eastern Europe and a bit later on in the season we also then had catastrophic floods in Pakistan around the monsoon belt.

So all of these weather patterns were actually related to the position of the jet stream and positioning of the jet stream is increasingly obviously related to Arctic warming and

melting of the Arctic ice caps, so it's a climate change impact. So one of the interesting things from thinking about extreme weather and how it's related around the world is that as you can see from the figure on the bottom left – the global map where it is red it is effectively where the bulk of the world's calories come from and the bulk of the world's calories come from a small number breadbasket areas. And given the chance of a bad year affecting more than one breadbasket we have a, quite a growing and increasingly obvious risk of multiple breadbasket failure which of course might impact upon food prices and food availability on a global basis.

The 3rd aspect of climate change which we haven't thought about enough because it is difficult to resolve from a model perspective is what happens to the world if we passed some sort of tipping point and change the way the climate works on a global basis. And just as an example of that, the top left figure the map with the red and blue lines on, is the depiction of the overturning circulations in the world. So this is the kind of water currents, the red and the blue are hot and cold water streams, and effectively these overturning circulations drive heat around the world in the oceans. And most of the heat that is trapped by global warming is stored in the oceans. And the top left portion of that map shows the overturning circulation in the North Atlantic, the Atlantic meridional overturning circulation (AMOC) and then the big map in the middle shows the distribution of heat if the AMOC switched off that we would lose from around the world. And effectively the overturning circulation that drives the Gulfstream brings around, as you can see from the blue colours, 8 or so degrees of temperature from the tropics around the Caribbean up towards Northwest Europe. And if the overturning circulation slowdown or turned off, for which there is some degree of evidence from climate models, if that were to happen of course north-west Europe would lose that heat benefit and if you think, if you go across north-west Europe to a similar latitude in northern Canada you're above Newfoundland, Labrador - no one lives there because the climate is so bad, certainly no agriculture. You could imagine a situation and back ofthe envelope calculation suggests that a 3rd of the world's agricultural production would be switched off were this overturning circulation to switch off. And I think if you look at the model predictions of how that might work there's probably something like 20% chance of that happening this century under our current conditions of global warming. So that's quite a scary thing.

So climate change is not just the average temperature it's not just changing extreme weather conditions it is also the potential for radical shifts might be quite sudden and irreversible in the way the global climate works and, of course, that will then feed into the way agriculture can function.

### *Climate change affects agriculture*

What does this mean for agriculture? Climate change clearly affects agriculture. This is a map from a relatively recent paper focusing on crop yields in wheat, rice, maize and soybean. From top to bottom under each of those panels ABC and D you have the areas of the world highlighted with the country outlines where the bulk of the calories are being grown. Alongside each of those countries there are bar graphs that show what the expected impact of yields are a range of different models, climate models, coupled to crop production models and those are the different colours of the bar graphs. And just looking whether you are thinking about wheat or rice or maize or soybean, from top to bottom, almost all of the bars are pointing downwards. So, on average, around the world

whether you're talking about any of the major cereals of which of course the bulk of the world's calories, to feed people and to feed livestock, come from the major direction is down. And it is down if you look at the maize graph, panel C, it is down by 10% in the Midwest, close to 10% in Brazil, somewhere around 5-10% in India and depending on the model 10 to 15% in China. So whichever way you look at it climate change is going to impact on the yields of the major crops.

And, of course, weather can impact, as the weather is changing, the weather can impact in many ways. Often we just kind of assume that it's droughts and temperature that matter but of course, as this table shows, rainfall can affect crops by waterlogging soil or affecting pollination or knocking flowers off trees and so on, changing humidity so more likely to get rust fungus diseases, flooding of course also does a whole range of things including impeding access to the land, so you can't actually get on the land to farm. Heat and drought increases stress, stops plants from producing their flowers, does a whole range of different things, slows down growth, plants go into dormancy and so on. Wind knocks crops over, affects port infrastructures, affects a whole range of different things to do with the access to inputs and so on. Clearly, snow, frost, hail can impact et cetera et cetera. Pests and diseases are changing and pests and diseases will change with climate change and whether extreme wind, for example, can blow pests into new areas. Climate change in general will change the envelope within which pests and diseases might existent, change their spatial distributions and so will impact upon crop losses and livestock diseases and so on.

And weather, of course, can impact with the inputs to agriculture particularly nitrogen fertiliser and the way the atmospheric pollution is formed, which can affect ozone which can the affect crop damage and so on and pollution in broad sense. So it's not simple and straightforward that the only thing that we have to worry about is extreme temperature. There are many aspects of changing weather that can impact on agriculture. And the second table, just for a UK perspective, just shows some of the different impacts for different fruit and vegetables that we grow here from high-temperature or in summer or in winter and either of those can matter from a plant growth perspective and therefore from a yield perspective.

So, some main messages from the perspective of how climate change will impact on crops yields and farm yields in general, including livestock. Wetter areas will get warmer and wetter, that is very clear from the climate models. Drier areas will tend to get drier and hotter, which is also very clear, and when rain falls it is going to become more extreme, so likely to lead to more flooding but in a broader sense it will also damage crops and tend to drown livestock and so on. Because it will become very intense soil erosion will be greater over-flooding of dams and irrigation schemes so damage to the infrastructure of agriculture and so on can be quite impactful in the future. And one of the issues that I think is under recognised by many people is that of course all these things can interact together and it's perfectly possible shown by the dot plot on the left-hand side it is perfectly possible for the weather to get more variable, perhaps because of the Jetstream impacts that I was talking about earlier, to get more variable. And so you can imagine a situation that as shown by this diagram on the left hand side that on average the weather is getting wetter or hotter or drier but the tail of the distribution is also getting wider so on average it is also getting drier or colder or whatever the climate variable might be, so actually when it come to planning the resilience culture it is not straightforward how it is not straight forward how its going to

work in any geography and therefore of course it is going to impact quite heavily on the way farming practice might work.

What does this all translate into? It translates into as shown in this diagram as you go from left to right from about now up to the end of the century what you can see for a whole range of different cereals and a whole range of different crop models what you can see is that the spread of the projections of the models is increasing over time. So the effect on average yields that I talked a few slides ago is one thing but the variability is likely to increase because the weather variability is going to increase. And models, I think, probably significantly underestimate this. Putting it another way, if you're planning from a national perspective a food system into the future it's very difficult to be certain that you will be able to grow the same sort of things in the same sort of away and expect year-on-year the same sort of yield. Much more likely is that what you're used to growing will become much more variable and so some years you'll have feast some years you'll have famine. And that variability in itself, and not just from a farmer livelihood perspective, but from a national perspective will become quite problematic as time goes.

And then from a farming perspective, of course, if you are an individual farmer on average if the weather and the seasonality is as it has been in the past then you can plan. If you can't plan very well then what you do? So this is just a cartoon of the weather variability is getting greater and yields are getting more variable so what you do? If you're in a situation where the variability is relatively small then what you would expect is that a farmer betting on the average conditions would do better than a farmer who tries to grow a whole lot of different things - to put eggs in various baskets rather than all their eggs in a single basket - and that shown by the normal condition specialist red and the variability specialist in green. But as you move from left to right in this cartoon and variability in yields or in financial returns increases, there will come a switching point, where if you're betting on the average yield being good from a kind of historical perspective if comes to well actually that bet gets realised every year, every other year, year third, every fourth year, at some point there will come a point where actually no longer expecting the weather to be normal and managing to grow different things in different ways and perhaps more diverse things that will start paying off when variability and returns increases, gets to the level that is probably fairly predictable at some point over the next decade or so. So actually if you are a farmer, what this means? I mean many farms around the world concentrate on growing a small number of crops and that in a sense is putting all of you eggs in one basket because if that crop fails then you have got nothing, whereas if you are a farmer who perhaps grows a range of different things, you might not get as much return when it is a good year but in a bad year you might be able to get some yield from some or all of your other crops as well as your main crop and so there is a trade-off which is called bet hedging in the literature, which means that you're more likely to do well under high levels of uncertainty but if the weather is entirely predictable and entirely normal you pay a cost which is shown in that cartoon. What I'm saying here is, of course, as the weather changes itself, farmers are likely to reach a point where they have to adapt their farming practice to manage their livelihoods.

One other point about climate changes is climate change is caused by carbon dioxide being put into the atmosphere and carbon dioxide is one of the base chemicals, of course, for photosynthesis so all things being equal if there's more carbon dioxide in the

atmosphere plants can photosynthesise at a greater rate, and this is called carbon dioxide fertilisation. And back in the old days there was quite an expectation that dioxide fertilisation would be a good thing because, especially in temperate latitudes, where we are not affected so much by extremes of heat, plants should be able to grow and yield more, and that is shown in this four panel graph. If you look no CO2 fertilisation the top 2 panels for a one and a half or two degree of climate change, in China you get relatively little impact from climate change. If you allow CO2 fertilisation in the models then yields actually increase for this example. So we used to think that CO2 fertilisation would be a very positive and a very good thing. Actually, of course, it depends upon the weather variability because if the weather's varying a lot then yields might not be anywhere close to the average projected yield. But the other thing, I think, that is really worth paying attention to, is that there is now quite a lot of evidence that as the CO2 fertilisation impacts, plants change their physiology because they're growing at different rates. And the changing physiology means that effectively the biology of how they make the grain, or the fruit or the vegetable changes. And increasingly we are seeing, and this is figure from a recent *Nature* paper by Sam Myers and his group, shows that for a whole range of different micronutrients - zinc, iron, et cetera - and macronutrient protein there are quite significant impacts on the nutrient content of the crop.

So when it comes to thinking about climate change, climate change is going to affect the mean yields, it is going to affect the nutritional quality whether it is meat or whether it is grain or whether it is fruit and vegetables. It is going to impact upon the variability and a lot of this is going to be determined by the variability of the climate, which at the moment we don't have a very good ability to predict.

And then final point in the section. Of course, when it comes to food systems, what we eat is an integral of what is grown locally, and what is grown far away. And the stuff grown far away is shipped around the world, traded around the world as this map shows, and when you look at global food trade what you can see is that there are a number of parts of the world where a very large amount of foodstuff or related -so fertilisers et cetera - small number of places where a large amount of the world's food supplies go. And if you look at, for example in the Midwest in the Gulf ports, 60% of US grain export goes through those ports. A few years ago we had hurricane Katrine. If hurricane intensity is increasing and hurricane frequency is increasing at some point one or other or multiple of these choke points might get disrupted and the ability to move stuff around might be interrupted.

And, of course, it's not just a drought that might create a global food price spike it might be a transport disruption coming about from weather or the interaction between weather and geopolitics. So, for example, you can imagine a situation where there is a local insurgency caused because of people moving because of climate change and migration into a country causing geopolitical disruption, which might then impact upon the way the trade routes in the Middle East work or something like that.

That's roughly an overview of how climate change will impact upon agriculture.

### *Agriculture's impact on climate change*

Now we need to look at how agricultural will impact on or is impacting on climate change. In the 2019 IPCC SRCCL – the special report on climate change and land - the latest figures were brought together for the way that agriculture created greenhouse gas pollution and that's what this table shows. The total amount of greenhouse gases emitted by humanity about 52 gigatons of carbon dioxide equivalent per year. Agriculture is responsible through land use change, so effectively removing rainforest primarily to grow soy in Latin America and palm oil in Indonesia, liberates about 5 gigatons of carbon dioxide a year over the last decade or so. Methane from cows and other ruminants and their rumen digestion, where the microbes break down the cellulose, and methane coming from flooded soil, primarily to produce rice, produce another 4 gigatons equivalent of carbon dioxide. Nitrous oxide, which comes from fertiliser, particularly synthetic fertiliser, which volatilizes and kind of evaporates and goes into the atmosphere and from manure and livestock urine counts for the 2.2 gigatons equivalent carbon dioxide. And then we have a figure of around 2.5-5 gigatons that comes from transporting food, manufacturing food, cooking food et cetera. So when all of that together the best estimate of the amount of carbon dioxide equivalents coming from food system is about 15 gigatons and so that's approximately a 3rd, 30% or so, of all greenhouse gases that humanity produces.

Now a third of greenhouse gases is quite a lot. If you think about what that means from a kind of human perspective - it's shown in this pie chart here - roughly speaking that blue wedge, 30% of food, is more or less equivalent to all lighting, all car transport, the chunk of air transport, all of washing machines and all heating and cooling used by people around the world. And, of course, you can imagine, from a climate change perspective, you can imagine changing our light bulbs to be low-energy light bulbs, moving towards electric vehicles on a global basis, insulating houses and reducing the need for active cooling using passive cooling or passive heating, and changing the energy efficiency in way we use energy in the home but once we've done all that the big weight of 30% of emissions from food is what we have left to play with. And, of course, part of the issue is that some of that food is wasted, about a third of that food is wasted. But in total half of that wedge comes from livestock and so, if we are going to reduce that wedge, one of the obvious ways that we can reduce that wedge on a global basis is eating less livestock.

### *Meat and livestock: a contentious issue*

And of course this is, on a political basis, a very contentious issue. Just looking at this in a little bit of detail, the issue of meat and livestock, this figure, here from a World Resources Institute report of a couple years ago looks by region - and it's the population up to about 2012 if I remember - on the left-hand side you have India, then Asia and then sub-Saharan Africa through to the US and Canada, on the right-hand side the width of the bar is the number people in that area and the height of the bar is the amount of protein that is available for people in that country. And the red is protein from animals and the green is protein from plants. And what you can see if you look at the 50g line, which is the thick line in the middle, that's the average daily protein required by humanity for a healthy life. And what you can see is that every region in the world on average there is enough protein and, of course, on average is not the same as everybody having availability of protein but certainly towards the right hand side people, consume much more protein than they need from a physiological perspective and as the population grows there is no real necessity from a nutritional perspective to say we

need to grow more food. And actually there is enough protein in the world already and probably looking at this graph, an oversupply of meat as opposed to plant protein.

When people say oh well the world is growing, the population is growing we need to grow more food, that's possibly not the case and certainly not the case from a livestock perspective. And then this figure looks at the footprint of producing a 100 g of protein in the 2 sets of panel a. The 1st 3 lines at the top are ruminant protein and then the 2nd batch of lines are for non-ruminant protein from crustaceans down to grain. And the columns are greenhouse gas emissions. So greenhouse gas footprint, land use footprint, then acidification eutrophication and water usage. The acidification, eutrophication are forms of pollution as well as being a gas emissions. Each grey bar shows the range of estimates in the literature for how many kilograms of carbon dioxide required to produce 100g of protein. So just looking at the beef, it goes from something like 20 kg up to about 100 kg with the black dot on average about 50 kg of carbon dioxide per 100g of Protein. The red line that goes down is the really interesting part of this graph and the red line is, given that variability, what is the most efficient form of ruminant meat production. So that red line is the top 10% of efficiency of production. And what you can see, if you follow the red line down, is that cheese, pig finish, poultry, eggs and of course protein from vegetables, it is all significantly on average less polluting than the top 10% of beef. And the middle of the beef production at 50 kg, if you compare that to, say, the middle of egg production, which is about 5 kg it's clearly an order of magnitude or so greater.

So whether you look at greenhouse gas emissions or land-use or even some of the eutrophication and acidification, when you look at the top of the graph you have big numbers, and when you look at the bottom of the graph you have small numbers. And if we want to eat healthily and eat a sufficient source of protein, if we choose to eat the vegetable proteins then we are eating a significantly much smaller land-use or greenhouse gas footprint food than if we choose to eat beef. So just from a dietary perspective if were eating less animal protein then we are having less of an impact on climate or land or someone. But, of course, the production of meat is not just a matter of greenhouse gas footprints or land footprints. My background is in ecology and wherever you look around grasslands in the world, you have, for example, this buffalo you have a major herbivores which as in human history we have always eaten. So the ruminants play an important part from an ecological perspective and of course they play a range of different roles from, ranging from a livelihood perspective - you know in many parts of sub-Saharan Africa the livestock are often the kind of financial bank they are the assets for a family in the absence of banks in a kind of Western sense. That's where all the value is stored from a family's perspective and it's their livelihood built around it.

From a landscape perspective often our culturally important landscapes are shaped by grazing regimes so if we removed a reproduction the world would change. Clearly from a social perspective for many communities around the world, family lives and important feast days are just that - feast days they are based around meals that are rich in livestock products. And then the picture on the top right is a poster for a France vs England rugby international and what they're showing there are 2 icons. The French cockerel and the English beef roast – the roast beefs the French call the English in rugby - and two food items are as important national symbols. So meat is clearly important on a global basis but the question is how much meat should we be thinking about eating and how should it be grown because about a 3rd of the world's grain is currently grown to feed livestock

for intensive livestock production with all the impact that drives including greenhouse gas emissions.

**The food system affects climate, is fragile to climate change, and doesn't provide enough nutrients**

So before I move onto the end, because it's important to say that we've got a food system that drives climate change, we've got a food the system that is increasingly fragile to climate change and we have a food system that doesn't work through many other lenses as well - whether it is because of biodiversity loss or soil degradation or reducing air quality or using water or reducing water quality but, from a nutrition perspective, I think there is a really important reason for thinking about reshaping the food system, which is not just because of the climate impacts. And that is that as we have gone through the last 70 odd years since the post-war Bretton Woods institutions were created - created international architecture of cooperation through the UN, the WTO, World Bank et cetera - the way we have driven the food system has been through economic liberalisation and a system based around driving down the prices and driving up availability and global trade has led to an extreme concentration of production in a relatively small range of crops in a relatively small number of places.

I showed this figure earlier about where the breadbasket areas are. And, if you look, now over 50% of the world's consumer crops come from what, rice and maize and if you add another 5, sugar, barley, soy, palm and potatoes, then that accounts for three quarters of the world's consumed calories. And they largely come from a small number of breadbasket regions in the world. And, of course, as we have driven up availability, we have driven down price. Increasingly around the world everybody is eating the same diets because that's what is most available and this has led to a homogenisation of diets around the world with a significant impact on public health. And just to illustrate that here's a figure from a recent paper on the left hand side is a dietary guideline from the United States, happens to be the Harvard healthy eating plate, and on the right-hand side is a figure showing what the world actually grows. And just looking at those 2 significant, significant differences the world radically overproduces by about 50% cereals and starchy crops, underproduces by about two thirds the amount fruit and vegetables that we need. Way, way overproduces sugar, because we shouldn't be eating very much at all and grows about 3 times more oils and fats primarily now palm oil and soybean oil and then perhaps doesn't grow as much legumes and protein crops as we should be growing.

So the way food system has been designed has been to produce calories cheaply but not to produce nutrition in the way that we should be producing and it is not a surprise that access, lack of access to good diets is now the number 1 factor that is driving both ill health and mortality on a global basis. And just to illustrate that, the figures are that about a tenth of the world's population will suffer from diabetes in the near future and the cost of dealing with diabetes, primarily through overconsumption of calories, the cost of dealing with diabetes is greater than the entire value of agriculture in the world. So we're driving the economy in the wrong direction.

And if you look in the UK our government's figures suggest that actually the ill health costs coming from poor diets are something like 3 to 5 times the value of agriculture to the economy. And that's just the dietary-related ill-health. Then if you think about

quality of contamination of water from bacteria from livestock production, zoonotic diseases you know like avian flu, antimicrobial resistance and so on, then the way we are producing food at the moment is not only bad for the planet but it is also bad for us.

So having said that we've got an agricultural system that impacts on the climate, climate change is making our agricultural system much more fragile. Our agricultural system is degrading the environment in many different ways and actually our agricultural system drives the food system, which does not provide nutritious diets on a global basis. What does this mean for the future?

### *The futures of food*

A range of recent reports in the IPCC - the land report, the global warming report and the Paris Agreement in 2015 – have two implications for our food system. The first as, mentioned earlier, is that when you look at our ability to decarbonise the food system, as shown in this panel here, the ability to decarbonise our food system particularly our livestock system which is the bit we're going to concentrate on now is about 2.4 gigatons maximum technical mitigation potential. What that means is that if we did everything that we could do to make our livestock farming as efficient as possible and reducing the greenhouse gases that come from the farming side it would save up to 2.4 gigatons. And as this figure shows actually if we changed our diets we could, from where we are at the moment, on a global basis we could save up to nearly 8 gigatons of greenhouse gases. And this primarily of course comes about by reducing the amount of meat that we might eat in the diet.

So the IPCC climate change and land report effectively says that if we're going to get anywhere close to Paris compliance global warming, so well under 2°, we can't afford for the world to carry on eating the sorts of westernised diets that the world is moving to on global basis and we have to think about being climate carnivores, flexitarian, eating meat a few times a week, a couple of times a week, rather than couple of times a day that happens in rich world.

The other implication of the Paris climate agreement is shown in this panel here, and it's a complicated panel, so I'll talk through it. If we are going to mitigate climate change, we have to decarbonise our emissions and that the track that we need to hit the Paris climate targets is shown by the green line. So that's our carbon budget for this century if we are going to be Paris compliant. Now there is no way on earth that we are going to follow that green line because we're just not ready for decarbonising our energy system, let alone decarbonising agriculture. So we're likely follow one of the dotted lines. And as you can see, the dotted lines up to about mid century are greater further up the y-axis than the green line. So that means is we're putting more dioxide into the atmosphere than we should do if we want to be Paris compliant. And what that means is that in the 2nd half of the century we have to suck that same carbon dioxide out of the atmosphere to get us back to what is called carbon neutrality. And the red dotted line, the highest red dotted line, dips down under the 0 line and ends are at eight and that eight represents the amount of land that we will need to grow biomass to suck carbon dioxide out of the atmosphere will be up to 8,000,000 $km^2$. And putting that in understandable terms that's about 2 1/2 times the size of India or is about the same as nearly 2/3 of all arable land in the world.

So what meeting Paris agreement suggests is that a) we have to change our diets to reduce our footprint to directly reduce our emissions but also if we're directly reducing our emissions by reducing the amount of land that we need for livestock production, which has big land footprint like it has a big climate footprint then that will potentially free up land which we can then use for biomass sucking carbon out of the atmosphere, coupled with CTS - carbon capture and storage. So we grow the biomass and then we burn it and we store it geologically, underground, in geological deposits. Or we can use the tried and tested plants technology and grow trees and store carbon in wood where it will be stored for a 100 or 200 years in the hope that we will then find some technical way of dealing with climate change into the future. But either way Paris suggests that we need to both change our diets and free up land, perhaps through changing our diets, to grow more biomass for climate mitigation itself.

In a sense, the same messages come from looking at the sustainable development goals, where land use and access to proper food occurs in all 17 goals to a different amount but the fact that we have a range of goals means that if we have to deal with zero hunger - so improving access to food at the same time as dealing with health and well-being, which is improving access to nutrition - whilst not undermining climate action, the Paris agreement, degrading life below water or life on land, et cetera, et cetera. So seeing all of the sustainable development goals together implies a significant transformation in our food system. And then this is increasingly coming out in the scientific literature, that we need to have a deep-rooted transformation of our food system.

The details of this figure don't really matter but I'll try going through it relatively quickly. The groups of columns, the vertical columns, are GHG emissions, crop land size, blue water use, nitrogen application, phosphorus application. Those are all planetary boundaries in fact. The rows are grouped in 3 major groups called baseline, guidelines, flexitarian - that refers to our current diets, healthy dietary guidelines diets and flexitarian diets, where there is a deliberative attempt to reduce the amount of red meat consumption. And within each block of those baseline, guidelines, flexitarian diets, we have baseline tech, tech plus, which is are we actually improving the technology of agricultural yields and production through sustainable intensification - 3 levels what we do today, a bit more of that and closing the yield gap significantly. And then within each one of those we have baseline, waste 2, waste 4 and the baseline is that we carry on wasting food in the way that we, waste 2 is we're reducing the waste by half, waste 4 is reducing the amount of waste a large amount.

What we want to do, obviously, given the vertical columns being planetary boundaries is find those lines were it's green all the way across. Only really the bottom one or two, and what that says is that we will only manage to live within planetary boundaries to do with land used, to do with greenhouse gas emissions, to do with water use and to do with biogeochemical cycling, if effectively we improve our technology, if we reduce waste and we change our diet significantly. And to do all that calls for a significant transformation in the food system, the way produce what we produce and the way we as citizens interact with it. And then just to make that point that our food system is deeply dysfunctional, following the Second World War and through the green revolution, of course, access to calories was a major problem. And we invested on a global basis significantly in improving yields to increase the access to calories.

And this set of graphs shows on the left-hand side as you improve cereal yields on the x-axis, food price on average, the blue dots and the blue line has come down, and at the same time the food price has come down and food availability per capita has increased. That's what we effectively set out to do following the Second World War. But of course as we have increased the calories available and reduced the price available this is increasingly leading to perverse outcomes. So here is similar data but instead of food price and calorie availability it is food waste in the left and panel and the prevalence of obesity in the right-hand panel. So as we drive up productivity of agriculture it drives down the price. It makes food economically rational to waste so the rate at which we wasted increases. And it makes it more available, calories are more available, so the rate at which we eat it because we're flooded with it - most people in the world have access to too many calories - and obesity is increasing. So what these graphs suggest is that a focus, a short-term focus, only on thinking about the food system, from a driving up productivity perspective particular of calories leads to negative outcomes.

And so you can think of this, our food system, as a set of vicious circles. But if we look into the future and think about business as usual and continuing to focus on sustainable intensification and productivity growth then we produce more cheaper food an that more cheaper food will drive more waste and ill-health. It will drive more climate change and that climate change will impact upon yields in itself but because we always expect cheaper food then we'll need more land et cetera, et cetera. If we carry on with business as usual, because we're driving more climate change, it increases land competition because we need more land for the carbon dioxide removal. So we have more competition for land and more competition for nitrogen, more competition for energy to run the system, more competition for water and achieve the sustainable intensification means that we end up with more uniform landscapes, growing fewer crops, less biodiversity and more intensive impact on soils, erosion et cetera, reduction in natural capital in general. And we make a system that becomes more fragile to that climate change and the perturbations that will come from that.

But image transforming the food system to do what we want it to do, which is feed people in a healthy and sustainable way. If we focused instead of agricultural productivity we focused on the efficiency of the food system -feeding people healthily in a way that doesn't put costs on the environment - we would naturally deal with waste. We would have a system where intrinsically we value the food for what it does to humanity. And that requires us in effect to pay the costs of production that are real, including environmental costs and avoiding the external costs that we put on the health system by making people ill by feeding them too many calories and not too much nutrition. So that all implies a greater recognition of the values associated with food. We would pay farmers more to grow less but differently. So farmers could invest more in sustainable production and not just ever increasing yields through intensification. If we were going to eat healthily, we would require a much greater diversity of food stuffs, particularly plants, that would require a diversified agriculture. We would need a more circular agriculture, perhaps more mixed farms. That would lead to landscape heterogeneity and more multifunctional landscapes. That potentially would lead to more rural employment and rural employment because farmers were getting rewarded more because we are paying them higher prices they would have more stable livelihoods. More efficient food system would make space for, because we're not growing lots of food to make us ill and throwaway, it would make space the climate mitigation. We could grow more, do more agroecology, we could grow more trees, we could do the carbon

dioxide removal and instead of driving a food system that is lacking resilience we could drive a food system that ended up creating great resilience.

So you can imagine, given that increasingly the world is waking up to the need to transform food system, you can imagine a food system that becomes better at feeding us and better at dealing with the environment and we'd end up as happier people on a healthier planet. Coming to an end there's a few conclusions. The food system was designed to deliver abundant food cheaply and this has had a whole range of negative outcomes. To a first approximation, particularly in the rich world but also increasingly in the developing world, eating a healthy diet is also eating a diet that can be sustainably produced within planetary boundaries. And that is one that is based on plant food primarily, some meat but not a lot, whole grains and particularly less in ultra-processed food and fats and starches and sugar. The SDG, the scientific literature, the Paris climate agreement, all imply rather deep-seated need to change to make our food system more climate compliance. And finally, really, unless we change the way we grow food and the way we interact with food we are locked into a regime of dangerous climate change and unsustainable land use, which in the long run will only harm us. And then a final point, the picture at the top left is a smallholder farmer growing tobacco in Malawi, and farmers often get blamed unjustly for being the bad guys in this piece because they are doing the wrong thing. And just as you can't blame a lady smallholder farmer sub-Saharan Africa growing tobacco reveals the tobacco industry and the ills of tobacco use, we can't blame on the farmers, just like consumers, are actors in the system and we respond to the way the food system has evolved and people have to make livelihoods. And the deep-seated transformation that we need in our food system requires that farmers be central to that and get rewarded for doing the right thing.

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