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Sustainable Production of Nutritious Food for Humanity: Food as the Nexus Between Human Health, Environmental Resilience and Social Equity

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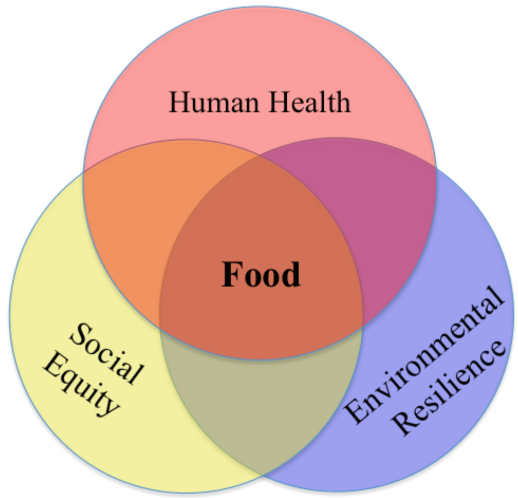

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Abstract

Humanity today faces environmental degradation and an epidemic of chronic human disease. A comprehensive, cross-disciplinary literature review was conducted to explore mechanistic links between these seemingly disparate challenges and test the hypothesis that solutions exist to simultaneously ameliorate environmental degradation and the global epidemic of chronic human diseases and disorders. Such links may render the concept of sustainability more tangible to the public, while exposing the preventable nature of common health conditions. Specifically, this thesis explores agriculture and food as links between human and environmental health. Evidence is summarized that the same agricultural practices that degrade the environment not only threaten future food security, but also produce nutritionally imbalanced foods that increase human disease risk. Mechanisms are identified through which unbalanced diets disrupt critical physiological processes and trigger today's chronic diseases and disorders. Knowledge of these links, and their ecological and evolutionary basis, can serve not only to prevent current problems, but also to achieve unanticipated gains in human wellness. The concept of sustainability is expanded to include – as inextricably connected – health of individual humans as well as their food plants and animals, the ability of the physical environment to renew itself, and the ability of human society to equitably serve all of its members. Sustainability becomes the method to ameliorate seemingly disparate challenges facing humanity, rather than being the end goal of such progress.

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Introduction and Background Information

When watching the news in the early 21st century, one inevitably encounters stories about climate change, mental health problems and violent behavior, and a rising epidemic of chronic diseases. Could it be that these seemingly unrelated topics have more in common than meets the eye? May careful examination of literature from different disciplines uncover avenues for solutions that begin to solve several current challenges to human society at the same time? In the present review, I focus on food as a common factor in human health as well as agricultural production systems. I will examine whether solutions in these two areas may be compatible or mutually exclusive, i.e., whether or not human society will have to choose between human health and the health of the environment. Through this literature review, I aim to elucidate and summarize links between environmental sustainability and human health – specifically focusing on the example of agriculture – that are currently neither widely acknowledged in an interdisciplinary context nor by the public at large. Some authors have discussed an apparent paradox of the *degradation* of the physical environment coinciding with *improved* global human health, and have sought explanations for this paradox (e.g., Raudsepp-Hearne et al. 2010). I will summarize evidence that inclusion of chronic diseases and disorders in the assessment of global human health can contribute to resolving the apparent paradox. <u>I will test the hypothesis that compatible solutions can be found that simultaneously ameliorate both environmental degradation and the epidemic of chronic human diseases and disorders.</u>

Background: Paradigm Shifts in Environmental Thinking

Leiserowitz et al. (2006) briefly summarized the historic development of thought on human-environment interaction over the past 30 years as a progression from seeing human development and environmental protection as mutually exclusive to acknowledging the two as interdependent forces (see also Clark et al. 2004). In the latter view, the physical environment – still protected for its "intrinsic value" (Leiserowitz et al. 2006) by some advocates – simultaneously becomes utilitarian as an essential, irreplaceable "life support system" for humans (see Leiserowitz et al. 2006 for a description of the resolutions of the 1972 Stockholm Conference, the 1980 World Conservation Strategy, and the 1987 Brundtland Report). As first established in the 1987 Brundtland Report, the environment is increasingly viewed through the lens of the emerging field of sustainable development (Leiserowitz et al. 2006; see also Clark et al. 2004) that aims to be a "reconciliation of society's development goals with the planet's environmental limits over the long term" (Clark and Dickson 2003).

However, despite several world conferences on environmental topics held by international organizations over the past decades, concern for the environment is still often perceived by the public as a concern of an activist minority who values nature above, for example, job development or economic viability (Schellenberger and Nordhaus 2004). My approach in this thesis is in agreement with the call issued by Schellenberger and Nordhaus (2004), in their widely noted publication "The Death of Environmentalism," that environmentalism should no longer be a special-interest concern of small groups of people. The latter authors bring a congruency of economic with environmental concerns to the forefront. In response to Schellenberger and Nordhaus, Dunlap (2006) suggests that the discussion of environmental issues in the context of economic issues is valid but not inclusive enough, and that additional criteria and solutions from the social and other realms should also be integrated (see also Leiserowitz et al. 2006). For example, a number of authors (Park et al. 2011; Capper 2013; Opp and Saunders 2013) define sustainability as the approach that meets goals of the "three E's": ecology, economy, and equity (with equity defined as fairness for all members of the global society; see also Costanza 2000; Leiserowitz et al. 2006 outlining the 2002 Johannesburg Declaration).

Adding Human Health to the Mix

To add to current discussions of sustainability focusing on either ecology *per se* or on ecology in the context of economic analyses, I will bring in a key focus on human health, with a consideration of social equity as an additional aspect. Scholars have bemoaned the fact that, as the definition of sustainability simultaneously becomes more specific and yet remains nebulous to many, the movement is not garnering enough needed support from the public because of its complexity and lack of imagery (Leiserowitz et al. 2006). These authors note how often a shocking event or "perceived crisis" is needed to mobilize the public towards ameliorative action on these issues (Folk et al. 2010). I propose that the effectiveness of the conversation about sustainability is often hampered by a lack of (i) urgency in present time as opposed to future threats, as well as a lack of (ii) perceived personal impact on an individual's family, and that connecting environmental issues to issues of present-day burdens of human disease and disorder could begin to galvanize the missing public commitment.

Without a doubt, the Brundtland Report's emphasis on preserving future environmental capacity to provide for humans (Leiserowitz et al. 2006; Clark and Dickson 2003; Clark et al. 2004) is an important addition to the conversation, but statements such as "The current unsustainable patterns of production and consumption must be changed in the interest of our future welfare and that of our descendants" (Leiserowitz et al 2006) do lack immediacy. A connection to *today's* welfare is needed to mobilize the current generations, whose actions today are required to implement improvements for future generations.

The results of the Millennium Ecosystem Assessment (2005) include a section linking long-term human health benefits to the sustainability of certain *ecosystem services*, such as food, freshwater, fuel, nutrient and waste management, processing and detoxification, climate regulation as well as cultural, spiritual and recreational services from ecosystems. All of these services depend on the *resilience* of ecosystems (and of the social systems to which the ecosystems are "inextricably linked"), with resilience defined as the "capacity… to continually change and adapt yet remain within critical thresholds" (Folk et al. 2010). An increasing understanding of ecosystem services and resilience has been accompanied by a shift in thinking away from top-down *command and control* management of natural resources that usually inadvertently resulted in decreased biodiversity and resilience (Holling and Meffe 1996). The latter practices are increasingly replaced by strategies such as *adaptive management*, in which principles of ecology play a central role and dynamic natural conditions are acknowledged and constantly monitored as the basis for management adjustments aimed at preserving the environment's resilience (Walters and Hilborn 1978; Gunderson 2000; Gregory et al. 2006; Kalamandeen and Gillson 2007). Arguably, humans should be free to adjust the earth to meet society's needs. But doing so in a way that does not undermine humanity's future will depend on a deep, interdisciplinary understanding of what our needs are (e.g., nutritionally and beyond) and how the environment itself can remain healthy to be able to support humans. Through this thesis, I will develop my own definition of sustainability, not as an end goal, but rather as an evolving approach that focuses on health in an all-inclusive sense – health of the environment, of individual humans, and of economies and societies.

From among the ecosystem services listed above, I will focus on those connected to agriculture as a system that plays a critical role in determining current environmental as well as human-health outcomes. I will take a different approach from that of Raudsepp-Hearne et al. (2010) who measured global human health based on the Human Development Index (the HDI, "an aggregate measure of life expectancy, literacy, educational attainment, and per capita GDP") and concluded that global health has improved over the last century while ecosystem services declined. Instead of placing emphasis on either the increasing average life expectancy or on the approximately 1 billion people who lack adequate access to food (Foley et al. 2011), I will focus on the physical and mental health of all people (including the other 6 billion people) and argue that everyone in the global community today is affected directly or indirectly by chronic human diseases and disorders. I will use the terms chronic diseases and disorders as synonymous with both non-communicable diseases as well as mental and learning disorders – two categories that are often separated even though they have common dietary and other lifestyle-related causes and should be targeted together as proposed by Jacka et al. (2014).

The general public today has a well-established acceptance that environment and health can be connected, via, for example, chemical exposure leading to birth defects (e.g., Love Canal disaster; Goldman and Paigen 1985), and is even ready to examine food as a possible contributor to our health problems. The latter readiness is evidenced by the widespread discussion of potential health risks from artificial creations such as GMO or *transgenic* crops (Nicolia et al. 2014), food dyes and artificial sweeteners (Bearth et al. 2014; Lindseth et al. 2014), trans fats (Willett et al. 1993), and others. However, do people commonly think of diet as linked to diseases like Alzheimer's or learning disorders, mood disorders, and violence? Not exactly (e.g., see Jacka et al. 2014). Through a review of mechanistic evidence, I will link these chronic diseases and disorders causally to food as a product of contemporary agricultural systems as influenced by (and, in turn, influencing) environmental conditions. My review will, thereby, identify the *current* burden of unsustainable food production practices on human health – while the emphasis in the literature on agricultural systems in a context of environmental degradation typically focuses on predicted future decreases in the global food supply and in ecosystem services on a global scale. The perspective offered in this thesis assesses how present agricultural systems play a key role in causing human diseases and disorders today, and integrates this information with threats to the future food supply (see Fig. 1). Viewed from this perspective, agriculture in itself becomes an important "leverage point" (Foley et al. 2011) for policy-making, and chronic diseases and disorders become a powerful current and relevant embodiment of the otherwise less tangible idea of sustainability. Images of a child with diabetes or attention-deficit hyperactivity disorder (ADHD) – or of a troubled school shooter – are specific, powerful, and concern people in the present.

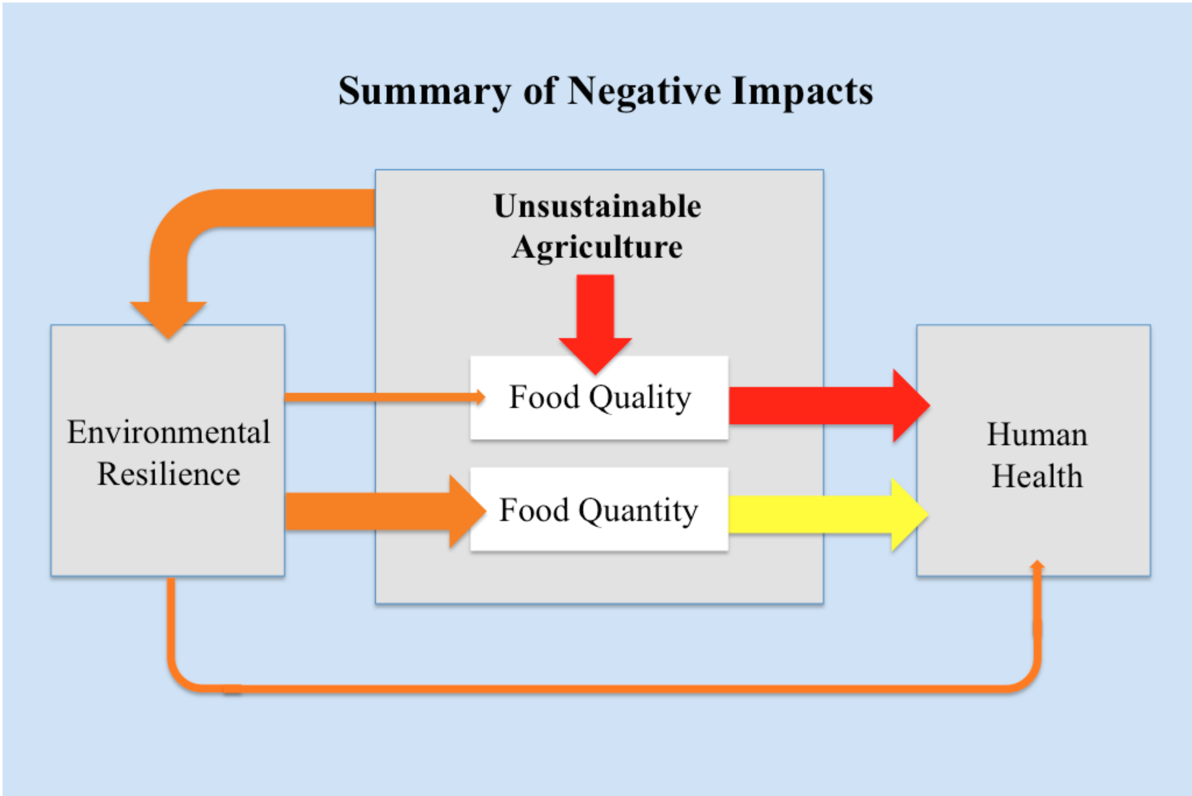

Figure 1. Schematic depiction of the negative impacts of unsustainable agricultural production systems on the environment and human health, as summarized in this thesis. Links are based either on *predicted future* outcomes (yellow), on *existing* impacts (red), or on current impacts predicted to intensify in the future (orange). Arrow thickness depicts the strength of the negative impact. The thin orange arrows depict negative impacts of environmental degradation and climate change on food quality (via the effect of rising atmospheric CO_2 levels on grain quality; Myers et al. 2014, see Chapter 3) and on human health (via pollution with toxins and antibiotics; see Chapter 2 and 3).

Figure 1 provides a schematic summary of the mechanistic links between environmental sustainability, as fostered by resilience, and human health that I will examine to evaluate whether pressing current human health concerns can serve to motivate a stronger public commitment to sustainability in a comprehensive sense. Figure 1 is actually consistent with the ideas of Raudsepp-Hearne et al. (2010) who posit that environmental degradation will only directly cause degradation of human health on a global scale in the future. I identify unsustainable agriculture as a cause of both environmental and health degradation, and illustrate what actions can and should be taken today. The tenet of my thesis is that current unsustainable agricultural practices are simultaneously the cause of (i) the poor *food quality* responsible for the current epidemic of chronic diseases and disorders and of (ii) the environmental degradation that is increasingly threatening the future food supply (*food quantity*). In turn, I will demonstrate that making agricultural production systems sustainable will simultaneously lower the current chronic human disease burden and foster environmental resilience. An understanding of the connections among human nutrition, human health, and sustainable practices may help the public as well as scholars from various fields to better capture the essence of sustainability.

By reviewing possible approaches to achieve immediate gains in human health via modified agricultural practices that simultaneously offer gains in environmental resilience, I hope to go beyond merely identifying problems and move towards concrete and principal solutions. This will also serve to demonstrate that viewing a problem from multiple angles can, in fact, make it easier to address a problem seemingly "too big" to tackle. Improving environmental resilience and human health on a global scale will require a shift in thinking towards considering multiple factors that pull in more stakeholders. Taking multiple factors into consideration is also necessary to generate viable solutions for various local contexts. Such comprehensive thinking is also needed to incorporate the additional dimension of social equity and to thereby achieve the ultimate form of sustainability that combines social and economic stability with human and environmental health.

Humanity may very well have reached an age in which, as some have suggested, "not only human action, but human thought and reflection on the consequences of its actions, would come to play a determinative role" (Clark et al. 2004). Change often requires a movement's alignment with "public values and attitudes, vivid imagery (focusing events), ready institutions and organizations, and available solutions" (Leiserowitz et al. 2006). This thesis aims to connect these critical pieces – as an example of how the complex issues facing society in the 21st century can begin to be understood and addressed by focusing on key mechanistic links among seemingly disparate issues.

Chapter 1
Environment and Agriculture

Many authors warn that current local examples of crop losses and slowing agricultural gains may point to serious threats to the future global food supply (Kirschenmann 2010; Newton et al. 2011). Conventional, industrial-scale agriculture (beginning after World War II) relies upon intensification and simplification (e.g., through cultivating single crops, or monocultures, in a given area) for its success in generating high food yield (Matson et al. 1997; Kirschenmann 2010; Foley et al. 2011). However, some warn that this success may be coming to an end as the conditions upon which its gains in productivity were based are changing (Kirschenmann 2010). Previous windows of unique weather stability are closing (Kirschenmann 2010) and the rising cost of the inputs required for conventional agriculture (e.g., fossil fuels for fertilizer and pesticide production for application on monocultures) contribute to dwindling profit margins (Kirschenmann 2010; Rains et al. 2011). Soil quality and freshwater resources are declining (Kirschenmann 2010). Crop losses due to the latter effects as well as to pests and extreme weather events (e.g., drought and flooding) exacerbated by climate change have already begun to threaten crop production in certain areas (Newton et al. 2011; Rains et al. 2011; Himmelgreen et al. 2012). Overall, gains in agricultural productivity are beginning to slow (Foley et al. 2011; Rains et al. 2011) as the human population continues to rise rapidly (Foley et al. 2011).

As will be elaborated below, not only do environmental conditions affect agricultural systems – conventional agriculture itself is a major contributor to climate change and environmental degradation (Foley et al. 2011), thereby generating a feedback loop and posing a threat to itself by damaging the very systems upon which it depends. Agriculture contributes heavily to CO_2 greenhouse gas emissions through, e.g., fossil fuel use, deforestation that eliminates trees as significant CO_2 sinks, and release of the greenhouse gas methane from grazing ruminants like cattle, to name the major contributors (Foley et al. 2011). The rising level of greenhouse gases contributes to climate change and weather extremes (Roberts and Bradley 2007) that negatively impact agricultural yields (Kirschenmann 2010; Newton et al. 2011). Moreover, agriculture currently relies on unsustainable freshwater supplies (irrigation accounts for 70% of freshwater withdrawals; Foley et al. 2011), and releases pesticides (that can kill more than their target organisms) and antibiotics into the environment. Conventional agricultural practices also cause disruption of nutrient (nitrogen and phosphorus) cycles through nutrient pollution from fertilizer runoff (Foley et al. 2011) and concentrated manure waste (Shepherd 2000). Over-fertilization of water bodies causes problems such as algal blooms, in the wake of which oxygen levels in the water plummet, reducing fish yields (Smil 2000).

In their authoritative review in the highly visible scientific journal *Nature*, which also led to extensive coverage by the same author in *National Geographic* (Foley 2014), Foley et al. (2011) suggest that food availability could be sustainably increased by a remarkable 100-180% by pursuing a few main target areas for corrective action: stopping the expansion of agriculture into new areas, increasing the productivity of existing agricultural land through intensive but innovative means (such as delivering only the required levels of water and nutrients), and cutting down on food that is wasted or devoted to biofuels or the feeding of animals. In addition, Foley et al. (2011) point out (as others have done since the 1970s; see Lappé 1971) that increasing the proportion of plant- versus meat-based foods would lead to a *reduction* in the environmental burden of agriculture through an *increase* in the efficiency of food production for human consumption per given land area. This phenomenon is based on the fact that each additional step in a food chain leads to a significant loss of the energy (calories) contained in the food organism as unusable heat energy; a much greater fraction of the original energy of the sun is contained in plant food compared to the calories contained in a cow that has consumed plants (see Odum 1968; Pollan 2006; Foley 2014). An investigation of calorie efficiency of various foods reveals that every 100 calories of grain fed to animals produces only 40 calories of milk, 12 calories of chicken, or 3 calories of beef (Foley 2014). Currently, "the land devoted to raising animals [directly or through producing animal feed] totals 3.73 billion hectares – an astonishing ~75% of the world's agricultural land" (Foley et al. 2011), some of which could doubtlessly be used to feed more people by shifting to production of plant foods for direct human consumption.

However, even from a purely environmental standpoint, the advice to shift diets towards plant foods should not be applied universally to all areas of the globe (see, e.g., Capper 2013; Wahlquist 2013). In fact, vast areas where grassland occurs naturally are incapable of supporting the growth of plants edible to humans due to high altitude (Gibbons 2014) or limitations in soil quality, topography, or rainfall (Wahlquist 2013). The only way for humans to obtain edible food from those land areas is by relying upon animals capable of converting the calories in grass and other pasture species to edible meat for humans (Pollan 2006; Foley et al. 2011; Flachowsky et al. 2013; Wahlquist 2013; Gibbons 2014) as pastoralists have done for centuries (McCabe 2008; Gibbons 2014). Ruminants, such as cows, sheep, goats, and deer use unique gut microbes to digest the energy-rich cellulose of grasses and other pasture species (producing the greenhouse gas methane as a by-product; see Chapter 3) that is indigestible fiber to all other animals including humans (Wahlquist 2013). An important fraction of land areas can therefore only produce edible food for humans via grass-fed ruminants. However, areas (e.g., in the tropics) capable of producing plant crops edible to humans should not be used to grow animal feed or biofuels (Foley et al. 2011; Wahlquist 2013).

In addition to careful land-use planning, the oceans need to be considered as a target for improved food production as they are a currently under-utilized source of food production – "Oceans cover 71 percent of Earth yet provide less than 2 percent of our food – for now" (Bourne 2014a). Marine farmers are currently looking for ways to make their practices sustainable (see Chapter 3). In terms of calorie production, farming of fish can, in some cases, be up to "7 times more efficient than raising beef," due to the fact that fish are cold-blooded and additionally use less energy resisting gravity because of water's buoyancy (Bourne 2014a). Discussion and development of promising options for how to sustainably produce large quantities of food is currently underway and growing, as summarized in the latest series of *National Geographic* articles entitled "The Future of Food" (May-December, 2014).

Reaching food security today and in the future will require an integration of the above-described information about climate, ecosystem services, non-renewable resource use, pollution, and efficient land-use and calorie production. An integrated understanding of the parameters surrounding environmental conditions and food production is needed for the identification of constraints and opportunities in designing sustainable agricultural systems. While agricultural techniques to increase food yields have often been applied without considering environmental impacts, environmentalists have, conversely, often ignored the need for food production – today, we need to integrate both perspectives and improve agricultural production in a sustainable way (Foley et al. 2011). Foley (2014) states,

> Addressing our global food challenges demands that all of us become more thoughtful about the food we put on our plates. We need to make connections between our food and the farmers who grow it, and between our food and the land, watersheds, and climate that sustain us. As we steer our grocery carts down the aisles of our supermarkets, the choices we make will help decide the future.

As a means to contribute to the development of such an "ecological conscience" as advocated by environmentalist Aldo Leopold (Kirschenmann 2010), I will next investigate human health as related to the environment through agricultural food production. In Chapter 2, the relationship between nutrition and human chronic diseases and disorders will be discussed. A subsequent synthesis chapter (Chapter 3) will integrate the conclusions on human nutritional requirements with those on sustainable agricultural and food system designs. Lastly, (in Chapter 4) I will argue that true sustainability is contingent upon taking into account local context and social equity.

Chapter 2
Food and Chronic Diseases & Disorders

Our agricultural systems determine what foods are produced and offered, while food, in turn, strongly impacts human health outcomes. Poor nutrition causes disability and loss of life that create economic burdens as well as human suffering (see below). This thesis focuses on the effect of diet on non-communicable, chronic diseases (e.g., heart disease, cancer, diabetes, neurodegenerative diseases like Alzheimer's or Parkinson's, and others) as well as mental and learning disorders (e.g., depression, schizophrenia, attention deficit, autism, and others). Non-communicable diseases are already responsible for more than 50% of the world's disability adjusted life years (DALYs), defined as years of healthy life lost to disability or death (Jacka et al. 2014). Jacka et al. (2014) elaborate that DALYs "account for 63% of global deaths and are predicted to cost the global community more than US $30 trillion over the next 20 years." The United Nations' World Health Organization is among those urging action to halt this huge negative global impact on "social and economic development" (Jacka et al. 2014). Therefore, human nutrition needs to be considered alongside environmental conditions when designing the agricultural systems of the future. What concrete evidence is there for a link between food and human health? And from what conditions is the global community suffering today?

All countries today are at some stage of what medical geographers term the epidemiological and nutrition transitions, indicators of the major types of health problems experienced across space and time. An epidemiological transition – from infectious disease to chronic disease as the prime concern – takes place as countries experience less famine, better sanitation and more "urban-industrial lifestyles" (Popkin and Gordon-Larson 2004). In addition, there is a close link between the epidemiological transition and a nutrition transition, characterized by a combination of reduced physical activity with increased consumption of sugary drinks and highly processed, sugary foods (Popkin and Gordon-Larson 2004; Baker and Friel 2014; see also Jacka et al. 2014). These nutritionally unbalanced foods – characteristic of later stages in the nutrition transition – contribute heavily to epidemics of chronic disease and disorders as well as widespread disability and early death (Popkin and Gordon-Larson 2004; Simopoulos et al. 2011; Jacka et al. 2014). Specifically, the latter foods provide excess free sugar and quickly digestible starches (these foods cause hyperglycemia = excessively high blood sugar levels, and are said to provide a high *glycemic load*), contain too much saturated fat, and are deficient in omega-3 fatty acids as well as in many micronutrients (e.g., vitamins and antioxidants). As will be documented in detail below (see Fig. 2), all of these nutritional imbalances have been mechanistically related to chronic diseases and disorders.

Developed countries are no longer alone in the experience of the epidemiological and nutrition transition – while the latter countries may have taken generations to shift towards current levels of low infectious disease and high chronic disease, developing countries are now rapidly reaching high levels of chronic disease (Jacka et al. 2014), even if still ravaged by infectious diseases (e.g., Reddy 2009). To measure progress in human development, society currently uses life expectancy, literacy, education, and per capita GDP (the HDI) and should now add the absence of chronic diseases and disorders. A more inclusive vantage point (along with the time delays described by Raudsepp-Hearne et al. 2010 and shown in Fig. 1) can offer an explanation for the "paradox" of degrading environmental conditions coinciding with apparent rises in global health levels. The rampant chronic diseases and mental disorders should thus be figured into existing analyses (Jacka et al. 2014), such as that done by Raudsepp-Hearne et al. (2010).

Apart from the above-noted correlation between changes in the quality of the food supply and human health, is there actual causal evidence that diet changes can effectively lower the risk for chronic human diseases and disorders? In clinical trials with thousands of participants who had already suffered an early heart attack, a traditional Mediterranean diet (low glycemic load, low in saturated fat, and rich in omega-3 fatty acids and antioxidants, see Estruch and Salas-Salvadó 2013; Parletta et al. 2013) dramatically lowered (by 72% over 5 years) the risk of second heart attacks (de Lorgeril et al. 1999). The Mediterranean diet also produced dramatic health benefits in studies of depression (Quirk et al. 2013), Alzheimer's (Singh et al. 2014; Jacka et al. 2014), diabetes (Koloverou et al. 2014), and other chronic conditions (Dauncey 2009).

Furthermore, causal links have also been demonstrated between diet and mental acuity as well as violent behavior (e.g., Schoenthaler and Bier 2000; Mysterud and Poleszynski 2003; Kaplan et al. 2004). In two rigorously designed studies by Schoenthaler and Bier, a daily combined omega-3 and antioxidant supplement significantly increased academic performance (Schoenthaler et al. 2000) and dramatically lowered (by 47%) antisocial and violent behavior in school children who received such supplements over a four-month period (Schoenthaler and Bier 2000). The rigorous design of this latter (placebo-controlled and double-blind) study included providing active supplements to some children, while providing placebo pills to the rest of the children, and withholding knowledge on who received active versus placebo pills from the children, teachers, and researchers until completion of the study (Schoenthaler and Bier 2000). The striking results of this study clearly establish environmental determinants of violent behavior beyond those associated with social climate (Baker 1988; Steffgen et al. 2013), exposure to violent video games (Anderson and Bushman 2001), access to weapons (Lowry et al. 1998), or genetic disposition (Ellis and Walsh 1997). In another study, Kaplan et al. (2004) administered large doses of mineral and vitamin supplements to 11 kids (ages 8-15 yrs) with a clinical diagnosis of bipolar disorder or severe ADHD. The participating kids exhibited pronounced, statistically significant improvements to the extent that, by several measures, the children could only be classified as borderline cases at the conclusion of the trial (using the same tests as before the supplementation began).

Based on the evidence from studies like those described above, it has become clear in recent years that dietary factors play a prominent role in human mental heath and behavior (for reviews, see Mysterud and Poleszynski 2003; Jacka et al. 2014; for an observational school behavior study, see Chavez et al. 1995). Furthermore, the classic *nature versus nurture* debate –

still widely discussed by the media and the public – has, in fact, been rendered all but obsolete by recent scientific advances in the study of epigenetics, the study of heritable changes in gene activation caused by environmental programming rather than heritable changes in DNA sequences (Ferguson et al. 2007; McKay and Mathers 2011). For example, maternal nutrition strongly impacts the fetus' risk for chronic diseases and disorders later in life (Davis 2011; Yajnik and Deshmukh 2012; for additional detail, see page 27 below). As will be discussed in depth below, diet determines the very composition of critically important human tissues, such as those in the brain. Furthermore, there is now evidence that lifestyle factors, such as unbalanced diet, pollutants (Parletta et al. 2013) and physical inactivity (Gomez-Cabrera et al. 2008; Egger and Dixon 2009; Jacka et al. 2014), over-activate key control genes of human metabolism.

Underlying Molecular Mechanisms for the Control by Diet of Health Outcomes and Behavior

There is public recognition that people today are getting sick in ways and to extremes previously unheard of, and many are wondering what has produced this change within the last century. We do live longer and consume larger portions of food that, combined with physical inactivity, lead to an increasing gap (a positive energy balance; Higgins 2014) between increased calorie intake and reduced calorie burning that results in weight gain – but there also appears to be something else going on. Such additional effects are the focus of the emerging field of nutrigenomics, studying the role of dietary factors in programming our genes (Müller and Kersten 2003). A recent study (Goss et al. 2013) demonstrated that people can put on increased levels of belly fat (*visceral obesity*) even when consuming overall fewer calories than their bodies are burning (negative energy balance) – these stunning data highlight the importance of diet *composition* and quality rather than just total calories. The latter findings are consistent with the implications of the nutrition transition that also points to diet quality, specifically an increase in consumption of processed foods, as related to an increase in chronic human illness (Popkin and Gordon-Larson 2004). Furthermore, the above results suggest that it is not simply overall obesity, but rather the specific distribution of weight gain along a person's waist that is related to chronic diseases and disorders (Roth et al. 2011; Goss et al. 2013). What underlying *molecular mechanisms* explain how diet heavily influences both physical and mental health outcomes? What might have possibly been going on inside the bodies of participants in the Mediterranean diet studies and in the vitamin supplement trials described above (Schoenthaler and Bier 2000; Schoenthaler et al. 2000)?

One of the major mechanisms by which diet influences human health is the provision of *essential* components that directly become constituents of our bodies. These essential nutrients cannot be produced in the human body and must therefore be consumed with the diet (Zhang et al. 2011). An example that relates to brain function and mental acuity is omega-3 fatty acids as well as antioxidants, both of which are required for producing and maintaining brain tissue and nerve function (e.g., through contributing to the structure of a major transport protein in the brain, the sodium-potassium pump, that is instrumental in establishing the conditions required for the generation of nerve impulses; Turner et al. 2003; Young and Conquer 2005; Hulbert et al. 2005; Parletta et al. 2013; see Box 1). While modern Western diets are highly deficient in omega-3 fatty acids (Simopoulos et al. 2013), good sources of the latter fats include cold-water fish (Simopoulos et al. 2013), eggs (Meyer et al. 2003), and nuts (Simopoulos 2002b). Some of the best sources of antioxidants are herbs, spices, chocolate, dark-colored berries, some nuts, vegetables including olive oil (Pérez-Jiménez et al. 2010) and red meat (Williams 2007).

Box 1. Production of Brain Tissue and Maintenance of Brain Function by Omega-3 Fatty Acids and Antioxidants

Dietary intake of omega-3 fatty acids (n-3) and antioxidants (AO) modulate the function of the sodium-potassium pump responsible for certain human brain functions (Turner et al. 2003; Young and Conquer 2005; Hulbert et al. 2005; Parletta et al. 2013). When it comes to neurotransmission and the fluidity of membranes of human nerve cells, only the *curved, flexible shape* of the n-3 fatty acid docosahexaenoic acid (DHA) – as opposed to the straight, rigid shape of saturated fatty acids – allows the sodium-potassium pump's shape changes underlying its pumping action (Parletta et al. 2013), which is the prerequisite for nerve action potentials as the basis for human thought processes. Reactive oxygen species (ROS) are reactive molecules (*oxidants*) that can damage various biologically important molecules (like membrane lipids) by oxidation, or the "stealing" of electrons, thus setting off a chain reaction by creating additional reactive molecules (Parletta et al. 2013). The very definition of an AO is a molecule that can prevent the oxidative damage of other molecules by itself giving up an electron while remaining stable (Parletta et al. 2013). Because oxygen preferentially attacks the double bonds that give n-3 fatty acids their important curved shape, high levels of AOs are needed to protect the n-3 fatty acids against oxidative damage. ROS are normally detoxified by AOs, which are needed in abundance to avoid disease. Mental, learning, and mood disorders have been linked to AO deficiency (Surh 2003; Kundu and Surh 2009; Malireddy et al. 2012) and n-3 deficiency (for both see Young and Conquer 2004; Parletta et al. 2013).

The omega-3 fatty acid DHA (see Box 1) is a critical component of the human brain, and should constitute 25% of the brain's grey matter (Valenzuela et al. 2006). DHA must be provided during fetal development (via the mother's diet), and within the first two years of life via nursing or supplementation (Valenzuela et al. 2006; see also Turner et al. 2003; Vidailhet 2007). Omega-3 fatty acid and antioxidant deficiency affect all brain functions and is thought to be involved in ADHD, depression, autism, schizophrenia, and neurodegenerative diseases (Young and Conquer 2005; Parletta et al. 2013) such as Alzheimer's and Parkinson's (Zhang et al. 2011). Without proper brain function in the form of proper generation of nerve impulses (action potentials), one cannot think clearly, cannot excel at academics, and might not know how to behave. Schoenthaler and Bier (2000) note that their

> Data do not imply that human behavior is not largely a learned phenomena…. However, for a minority of children, neither rewards nor official sanctions produces conformity… for this minority, undiagnosed and untreated malnutrition may be impairing their brain function to such an extent that normal learning from discipline does not occur.

Aside from serving as critical body constituents, dietary nutrients also play a role in gene programming. Could it be that most of the major chronic health conditions of today have some underlying commonality? While a remarkably high number (from tens to hundreds of thousands) of original research articles exist in the nutritional literature on these diseases, a majority of these articles focus on a single disease and a single nutritional factor, such as heart disease and cholesterol, diabetes and sugar, colon cancer and fiber. When this body of literature is viewed collectively, as done in the present thesis, a more comprehensive picture emerges. A few key dietary nutrients influence human health by modulation of human metabolism and immune system response (see Fig. 2). The human immune system is "often up-regulated by nutrition-related signals, independent of the actual presence of a pathogen" (Roth et al. 2011). The costly immune response (requiring a considerable investment of energy) has evolved to be proportional to the available energy reserves (in the form of belly fat), presumably to match the defense response to the energy available for expenditure (Okin and Medzhitov 2012; Wells 2012). Fat storage in mammals in response to cues in the external environment presumably evolved as a mechanism for survival in environments with changing seasons (Lev-Ran 2001). The fall season would have been the time of year with plentiful fruit availability, during which humans would have naturally encountered plant foods like berries with high levels of free sugars as well as food animals with saturated fat stores. Consumption of these seasonally available, energy-rich foods promoted fat storage around the belly and increased survival through the winter. Today, people are becoming obese as they consume foods high in saturated fat and free sugar year-round.

Due to the link between the extent of energy storage and the strength of the immune response, excess energy storage as belly fat over-stimulates the human immune system (visceral fat cells make signal proteins, cytokines, that activate inflammation; Tzanavari et al. 2010; Farooqui et al. 2012; Gilbert and Slingerland 2013). A continuously over-active immune system causes chronic low-grade inflammation (Tzanavari et al. 2010; Gilbert et al. 2013). Most of the chronic human health conditions of today have been demonstrated to be *proinflammatory* diseases and disorders, caused by chronic, low-grade inflammation, in which the overactive immune system attacks the body's own nerve cells, heart cells, insulin-producing cells, and others, thus contributing (along with oxidative stress, e.g., see Box 1 and Fig. 2) to neurodegenerative diseases and heart disease (Michaud et al. 2013), autism, depression, schizophrenia, ADHD, heart disease, diabetes, cancer, and others (see Roth et al. 2011; Jacka et al. 2014; Gibney and Drexhage 2013; Parletta et al. 2013). What are the specific dietary (and other lifestyle-related) causes of this immune-system dysregulation?

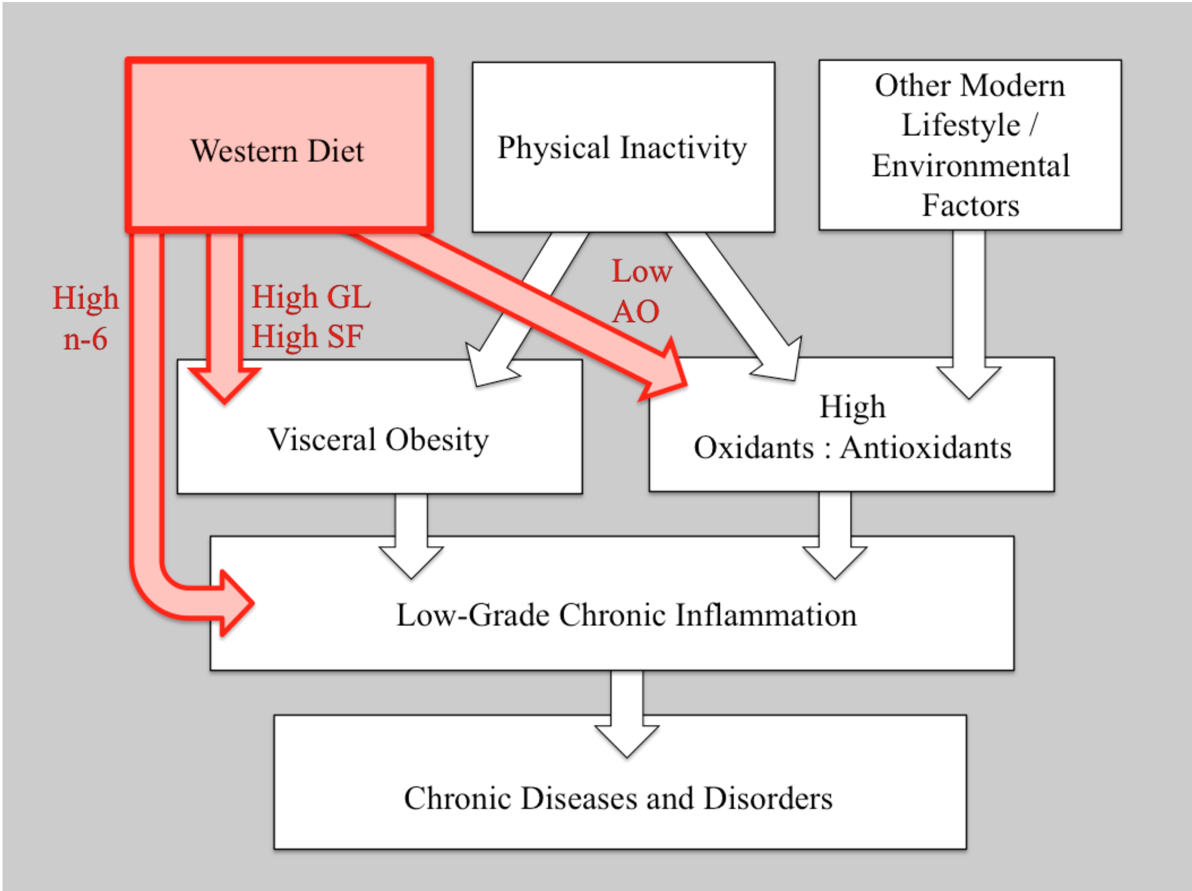

Figure 2. Schematic depiction of synergism of specific elements of the modern Western diet (red box and arrows: high glycemic load [GL], high saturated fat [SF], excess omega-6 fatty acid [n-6], low antioxidants [AO]), physical inactivity, and other lifestyle-related factors in triggering chronic diseases and disorders by causing low-grade, chronic inflammation (immune system dysregulation) via a stimulation of visceral obesity and a shift of the body's internal balance of oxidants to antioxidants to the oxidative side. "Other modern lifestyle / environmental factors" producing high levels of oxidants include stress, too little sleep, pollution and toxins (e.g., from pesticides), smoking, drugs, and excessive drinking (see below).

The modern Western diet promotes visceral fat accumulation by providing excessively high levels of saturated fat (Summers et al. 2002; Krachler et al. 2009; Teng et al. 2014) and glycemic load (Brand-Miller et al. 2002; Goss et al. 2013) and thereby produces an exaggerated version of our bodies' evolved response to intermittent times of ample energy supply (Roth et al. 2011). Western diets also provide a highly unbalanced ratio of omega-6 to omega-3 fatty acids, resulting from a deficiency in omega-3 fatty acids combined with an excess of omega-6 fatty acids (Simopoulos 2008, 2011, Simopoulos et al. 2011, 2013). Essential polyunsaturated fatty acids (e.g., omega-3 and omega-6) are converted by the human body to hormones that regulate the immune system, with omega-6 becoming stimulators of the immune response and omega-3 becoming anti-inflammatory (Calder 2006; Galgani and García 2014; Teng et al. 2014; see also Simopoulos 2002a; Simopoulos 2008; Gordon and Bazan 2013; Ilich et al. 2014 for the link between obesity-related inflammation and a lack of omega-3 fatty acids). The modern Western diet furthermore provides insufficient levels of dietary antioxidants due to low levels of fruit and vegetable consumption (Parletta et al. 2013). Dietary antioxidants dampen the immune response while oxidants heighten it (González-Castejón and Rodriguez-Casado 2011; Das et al. 2012). Consequently excessive levels of unopposed oxidants in the body increase the risk for inflammation-related chronic diseases (Surh 2003; Kundu and Surh 2009; Malireddy et al. 2012). Figure 2 illustrates how the key components of the modern Western diet synergistically produce chronic inflammation. In contrast, the Mediterranean diet has been shown to have an anti-inflammatory effect, which is likely the reason for its effectiveness in lowering the risk for chronic diseases and disorders (Kontogiorgis et al. 2010; see also Parletta et al. 2013).

Although a major player in determining disease risk (e.g., Jacka et al. 2014), diet is not the only lifestyle factor that influences human health: physical and/or mental stress, too little sleep, pollution and toxins (e.g., from pesticides, see link in Fig. 1), smoking, drugs, and excessive drinking all produce high levels of oxidants and promote inflammation (Egger and Dixon 2009; Smilin Bell Aseervatham et al. 2013; Parletta et al. 2013; see Fig. 2). For example, while certain antioxidants in the body must be acquired through diet, others (antioxidant enzymes) are produced by the body itself in response to the oxidant triggers generated by working muscles (Gomez-Cabrera et al. 2008). Moderate and regular exercise is thus important, while both physical inactivity (Jacka et al. 2014) (too few oxidants produced to stimulate the endogenous antioxidant enzymes) and excessive exercise (excessive oxidants produced) lead to undesirable outcomes (Egger and Dixon 2009). Humans are currently experiencing an unfavorable combination: the modern environment and lifestyle produces excessively high levels of oxidants while the Western diet is deficient in antioxidants. In conclusion, to function normally, our bodies require balance of oxidants (those produced internally during muscle contraction) and antioxidants, and the right ratio of omega-3 to omega-6 fatty acids at levels causing neither deficiency nor excess.

It is becoming clear that the modern environment has recently changed so much from the environment in which humans evolved that human metabolic responses are being derailed, resulting in disability and disease. At the same time, the recent breakthroughs in the understanding of diet-gene interaction have the potential to serve as an opportunity for achieving unprecedented levels of human wellness via informed lifestyle management. For example, improving the diet of pregnant women is a promising example of lifestyle management that could offer amplifying gains in the health of entire populations (Yajnik and Deshmukh 2012). As briefly mentioned earlier, maternal nutritional status profoundly affects fetal development and additionally can even lead to a semi-permanent programming (epigenetic programming) of gene activation patterns of the offspring that last into adult life (Davis 2011). For example, maternal nutritional imbalances can lead to the phenomenon of the “thin-fat baby” with an accumulation of visceral fat irrespective of birth weight associated with greater risk for diabetes later in life (Yajnik and Deshmukh 2012). Can humankind successfully combine this knowledge of evolved, unalterable responses of human metabolism to diet with the emerging understanding of what governs sustainability of our food supply?

Chapter 3

Congruencies Between Prevention of Chronic Disease & Disorders and Achieving Environmental Resilience

Pioneers in their respective fields are beginning to tie together research findings from different disciplines, as did participants in a 2010 conference entitled "Action Plan for a Healthy Agriculture, Healthy Nutrition, Healthy People" (Simopoulos et al. 2011). Chapter 3 will identify key limitations of current agricultural practices in providing nutritious and sustainably produced foods, and suggest that these limitations should be the top targets for improving agricultural practices from a combined environmental and human nutrition perspective. From both of the latter perspectives, current practices of both crop- and livestock-rearing need to be redesigned. The present analysis identifies approaches that promise to simultaneously foster human health (by lowering the risk of chronic diseases and disorders via production of foods of high nutritional quality) and environmental sustainability and resilience (through practices that preserve and enhance ecosystem services). These latter approaches include utilization of already available resources as well as post-modern technological approaches that offer intensive, yet sustainable practices (Pollan 2006, see Box 2). Figure 3A summarizes key negative impacts of current agricultural practices on both human health and the environment, while Figure 3B highlights suggested changes to these practices that promise to foster environmental resilience as well as human health. Figure 3 draws upon information in the previous chapters as well as information provided in this upcoming chapter.

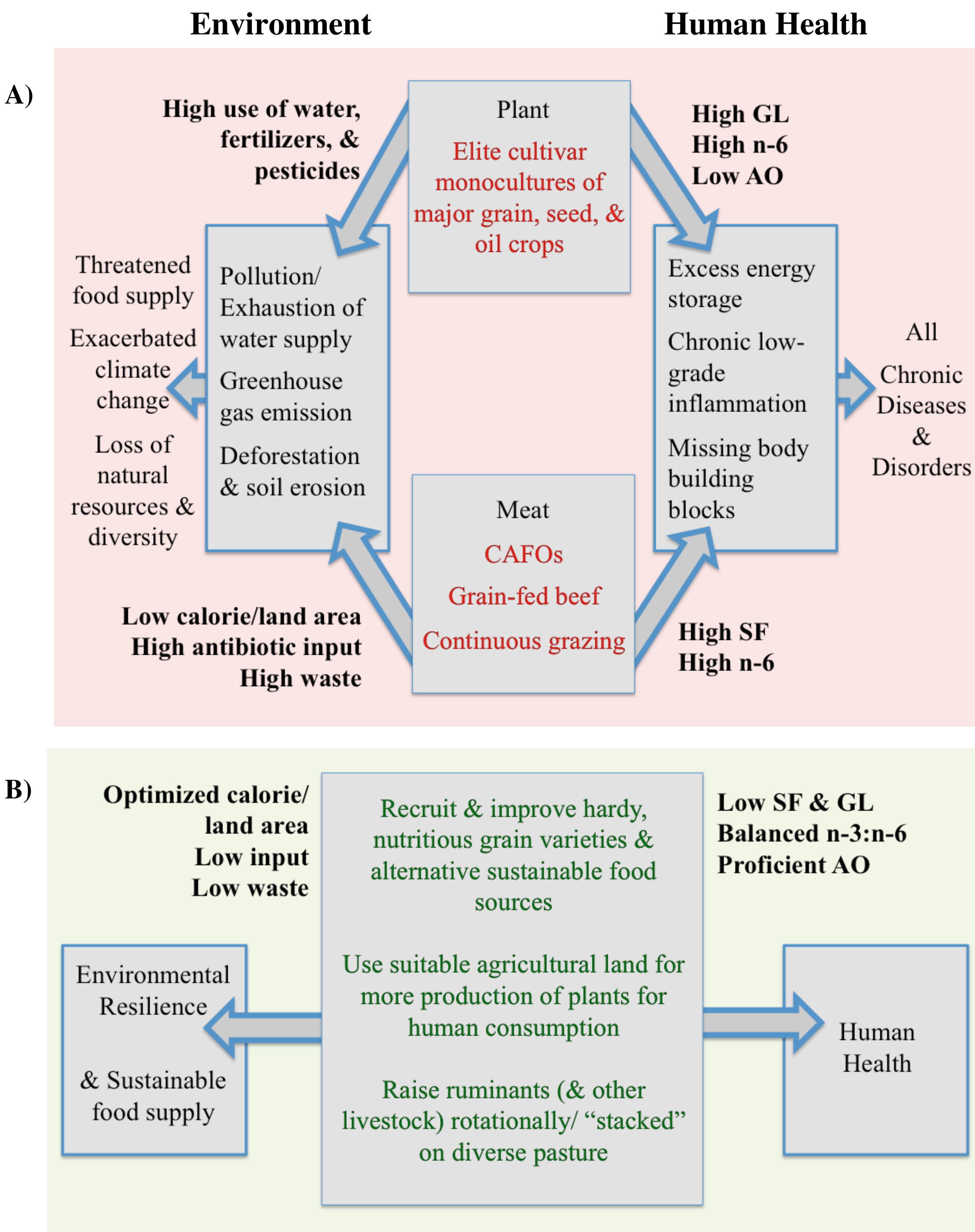

Figure 3. A) Schematic depiction of two key factors, conventional crop and livestock production (red), that contribute simultaneously to environmental degradation (left side, “Environment”) and elevated chronic-disease & disorder risk (right side, “Human Health”); B) Suggested changes for improved practices in green. GL=glycemic load; SF=saturated fat; n-6=omega-6 fatty acids; n-3=omega-3 fatty acids; AO=antioxidants; CAFOs=concentrated animal feeding operations.

Modern Elite Crops

It is well established that the extensive processing of food that is common today leads to poor nutritional quality of the resulting food products, which, in turn, increases the risk for chronic diseases and disorders (e.g., low antioxidants and high starch and therefore glycemic load; see Figs. 2 and 3). Insufficient intake of vegetables and fruits exacerbates these effects. However, there is also evidence that even the fruit and vegetables grown through conventional agriculture are lacking in nutritional quality (Yang 2006; Robinson 2013) as a result of the criteria used for choosing crop species, for further breeding these species, and for determining crop-growing conditions (see below). The modern approach to conventional industrial-scale crop production has increasingly centered on monocultures (see Chapter 1) of *elite crop cultivars* (intensively bred cultivated varieties used in agriculture) selected via intensive breeding programs and grown under conditions that produce large plant or fruit size, uniform appearance, and durability (Foley 2014). It turns out that selection using the latter criteria has come at a high cost to (i) nutritional quality and flavor (Foley 2014; Jabr 2014) as well as to (ii) the plants' resistance to drought and other environmental stressors (Newton et al. 2010).

This trend has resulted in nutritionally unbalanced plant-based foods that, for example, contain excess levels of free sugars and quick-burning starches, leading to a high glycemic load (Robinson 2013; see Fig. 2 for health impacts). As stated by Robinson (2013), who compares the nutritional quality of various crop varieties such as early and modern corn cultivars, "Ever since farmers first planted seeds 100,000 years ago, we've been unwittingly selecting for plants that are high in starch and sugar and low in vitamins, minerals, fiber, and antioxidants." Human evolution presumably favored a palate for mild-tasting foods with high levels of sugars, starch or saturated fat that contributed to beneficial fat accumulation, e.g., in the fall (see Chapter 2), and avoided excessive levels of astringent-tasting, potentially toxic plant chemicals (that include antioxidants; see explanation below). While humans have been breeding their crops for these features since the beginning of agriculture, it is becoming clear that we have finally taken crop breeding a step beyond what is compatible with human health (Robinson 2013). In addition, the feedback loops (see Fig. 1) of unsustainable agricultural practices contributing to increased greenhouse gas emission and climate change that threatens future agricultural production itself also include a specific feedback of elevated atmospheric CO_2 levels on crop nutritional quality that lowers, for example, levels of the minerals iron and zinc in grains (Myers et al. 2014). Furthermore, the emphasis of conventional agriculture on a few species of grain as major staples and on mass-produced vegetables has led to an imbalance in omega-6 to omega-3 fat composition since the major grain species, and oils from crops like corn, sunflower/safflower, soybean, and cottonseed, happen to feature extremely high omega-6 to -3 ratios (as opposed to, e.g., canola oil; Simopoulos 2002b). All of the imbalances listed above in the nutritional composition of modern staple crops increase the risk for chronic human diseases and disorders (see Fig. 3A as well as Chapter 2 including Box 1 and Fig. 2).

Declining nutritional quality and flavor due to low antioxidant levels are also associated with a concomitant problem of declining plant resistance to drought and other environmental stressors. This connection between plant nutritional quality and plant stress tolerance results from the fact that the same plant chemicals that impart flavor and serve as antioxidants in the human body function in the plant as defense compounds against physical (abiotic) and biological (biotic) stresses present in the environment (for mechanistic explanations, see Foyer and Noctor 2013; Kopczewski and Kuzniak 2013). These antioxidants – as flavorful, bitter or astringent-tasting plant components – have been lowered in their concentrations or removed altogether via intensive crop breeding (see above) and conventional agricultural growing conditions (see below). The U.S. Department of Agriculture reported a decline in various nutrients (including the antioxidant vitamin C) in 43 crops between 1950 and 1999 (Davis et al. 2004).

Typically, plants grown without ample irrigation or without protection by pesticides protect themselves naturally through synthesis of antioxidants for their defense against abiotic and biotic stress (Hounsome et al. 2008; Gill and Tuteja 2010). Modern crop cultivars have been selected under conventional agricultural conditions of ample water supply, ample fertilizer supply, and heavy pesticide use. As a consequence of selection under these high-input conditions, modern cultivars possess a lower capacity to synthesize antioxidants for their defense (Newton et al. 2010) than traditional cultivars (or *landraces*) not subjected to "a formal breeding programme" (Bitocchi et al. 2009). The modern cultivars thus exhibit a lower tolerance to drought (and other abiotic stresses) and a lower resistance to pests and pathogens as biotic stresses (Newton et al. 2010). Low antioxidant levels at once make elite crop cultivars more vulnerable to fluctuations in their environment and also fail to make the plants nutritious – high levels of antioxidants are required to provide essential inputs into human regulatory gene networks, specifically the critical balance between oxidants and antioxidants (Hounsome et al. 2008; Gill and Tuteja 2010; see Fig. 2 and Fig. 3A above).

Once again, just as humans evolved a keen taste for starch and saturated fat when these energy-rich food components were rare in the ancestral environment, there was reason to develop taste aversions to extremely high levels of antioxidants (bitter or astringent foods) because antioxidants, as plant defenses, act as toxins aimed at killing small insect herbivores by inhibiting cell division and immune response in the herbivore (e.g., see Cespedes et al. 2004). One can speculate that human cell-division rate and immune responses evolved to function in the presence of substantial levels of dietary antioxidants. It is clear that a deficiency in dietary antioxidant supply leads to excessive cell-division rates and an excessive immune response (chronic, low-grade inflammation; see Fig. 2), demonstrating that balanced levels of dietary antioxidants are required to maintain human health (see Chapter 2).

Today, however, our foods provide insufficient antioxidant levels to foster health (Fig. 2 and Fig. 3A; Robinson 2013). Beyond their high levels of health-supporting antioxidants, traditional crop cultivars, from which modern cultivars were originally bred, typically also exhibit a greater ability to extract water and mineral nutrients from the soil than elite cultivars. For example, the traditional cultivars' ability to form effective symbioses with soil microbes has apparently been lost in elite crops bred and grown under conditions of ample water and fertilizer supply (Newton et al. 2010). The trend of increasing dependence upon high external inputs, while concurrently decreasing resistance of elite crops to limiting or variable water supply, is particularly worrisome in light of dwindling freshwater reserves and the increasing temperature extremes and drought events accompanying climate change (see Chapter 2). In conclusion, it is both the selection and the intensive breeding of modern crop varieties as well as the actual high-input crop growing conditions that decrease the use-efficiency of physical resources, cause pollution (thus lowering environmental resilience), and lower crop nutritional quality (and thus increase the risk for human disease and disorders).

Nutritional quality, as measured by total fruit antioxidant content, has been shown to be inversely proportional to fruit size as demonstrated by Hanson et al. (2004) for a large number of tomato cultivars. Does greater nutritional quality thus come at the cost of reduced crop yield? There is evidence that increased nutritional quality and flavor can actually be achieved at no cost to yield. Winemakers are already employing controlled reductions in water supply (*precision* *irrigation* or *regulated deficit irrigation*) to enhance the grapes' production of flavorful antioxidants *without* any reductions in grape size (Acevedo-Opazo et al. 2010; see also Teixeira et al. 2013). Another encouraging example for the feasibility of combining desirable traits, such as high yield with superior stress tolerance, is the successful breeding of crosses (Yadav 2008) between (i) local traditional millet cultivars (exhibiting superior drought tolerance, but lower yields under well-watered conditions) and (ii) modern elite millet cultivars (exhibiting low drought tolerance, but higher maximal yields under well-watered conditions). Remarkably, the resulting hybrids exhibited higher yields than either plant parent under *both* drought and well-watered conditions (Yadav 2008). While Yadav (2008) does not explicitly address millet antioxidant content, it is likely that drought tolerance is associated with higher antioxidant levels in millet as well. Such associations have been demonstrated for a number of traditional crop cultivars that combine desirable nutritional quality with a superior abiotic and biotic stress resistance and are grown by local communities in large parts of the world – such as the grain crop quinoa that exhibits high drought and salinity tolerance and simultaneously provides all amino acids essential for humans along with high antioxidant levels (Ruiz et al. 2014).

Another congruency between fostering resilience and prevention of chronic health problems (see arrows of Fig 1) lies in the fact that highly pest-resistant crop species and varieties not only tend to offer greater nutritional quality but promise to further benefit human health by requiring lower or no inputs of pesticides toxic to humans (some pesticides act as oxidants, see Chapter 2, Fig. 2). It is well established that chronic pesticide exposure can negatively impact neurological function and can increase the risk of cancer, birth defects, and other adverse outcomes (NRDC).

In addition to conventional crop breeding and the actual growing conditions used for intensive crop production, food processing and meal-composition choices have profound implications for human health (and, by association, also for the economy, as well as social equity, as briefly visited in Chapter 4 below). Processing of grain removes some or all antioxidant minerals and vitamins that reside mainly in the grain's outer bran layer (Tiwari and Cummins 2009; Van Hung et al. 2009). Meal composition – what type of food and how much of each food is eaten by an individual – also has a tremendous impact on both health and the environment. This consideration brings us back to the debate over plant- versus animal-based foods. Just like the current intensive production of elite crop cultivars, the current intensive practice of livestock rearing is unsustainable with respect to both human health and the health of the environment.

Modern Intensive Livestock Rearing

Much like elite crop cultivars, grain-fed beef is inefficiently raised on high inputs, produces waste that degrades the environment, and does not provide the nutrients needed to foster human health. In fact, consumption of grain-fed beef, usually raised in concentrated animal-feeding operations (CAFOs), is causally involved in the health problems of its human consumers (see below). Therefore, when it comes to addressing human-health concerns, climate change, and land-use efficiency, a vocal group of authors and activists argues for a drastic reduction in overall meat consumption (Stehfest et al. 2009; Carlsson-Kanyama and González 2009), especially red meat from cattle that, as ruminants (and in contrast to poultry and pork), produce the greenhouse gas methane. The traditional Mediterranean diet, lauded for its health benefits, does indeed consist largely of plant-based foods with some seafood and poultry, but very little red meat (Estruch and Salas-Salvadó 2013). However, those who cite the benefits of the

Mediterranean diet as evidence for the health benefits of eating less meat (especially red meat) may be missing an important distinction, i.e., that what matters, when it comes to human health and environmental health, is *how* (see Pollan 2002; Dawson et al. 2011; Wahlquist 2013) and *where* meat is produced (see Foley et al. 2011; Wahlquist 2013).

As depicted in Figure 3A, *CAFO-raised, grain-fed* beef is unhealthful due to its unbalanced, excessively high ratio of omega-6 to omega-3 fatty acids (Dawson et al. 2011; as a result of the high omega-6 content of the grain feed; Simopoulos et al. 2013) and its high saturated fat content (as a result of the cattle's lack of physical activity and consumption of high-calorie supplemental feed such as starchy or high-fat grains or fat supplements, all leading to a positive energy balance; Pollan 2002). Furthermore, the raising of animals in crowded, confined lots (and feeding them, e.g., corn that increases ruminant stomach acidy to harmful levels, Pollan 2002) gives rise to diseases and infections that require high antibiotic inputs (Pollan 2002). CAFOs also produce very large volumes of concentrated animal waste that cannot be sustainably recycled into the environment – the CAFO-based system in the U.S. currently produces 130 times the amount of waste produced annually by the human population of the U.S. (Shepherd 2000). In contrast, *grass-fed* beef (and meat from all other types of ruminants) produces calories from food (grasses, other plants) indigestible to humans (see Chapter 1), is healthful for humans due to its low saturated-fat content, its high vitamin and mineral/antioxidant content, and its balanced ratio of omega-6 to omega-3 fats (Alfaia et al. 2006; Williams 2007; Dawson et al. 2011; see Chapter 2), and can be produced with low inputs and low waste. Examples already exist today of farms designed by innovators, where, for example, beef production is integrated into holistic approaches, including multiple crop and livestock species, based on the principles of ecology and evolution. These examples include the *Polyface* farm described in Michael Pollan's book *The Omnivore's Dilemma* (see Box 2 on *Polyface* farm), the Fairlie farm (Fairlie 2011), as well as several other types of model agroecosystems, such as the wetland fish farm Veta la Palma (Kloskowski et al. 2009) and ecology-based fish farming in the ocean (Bourne 2014a).

An *agroecosystem* is based on the principle, described by Rains et al. (2011), of how natural ecosystems become established along an S-curve of growth, where the initial phase features single or a few species whose growth and survival is driven by external inputs. Over time, a state is reached in which species diversity and interactions are high and external inputs are no longer needed. Conventional agriculture plows the land every year "forcing the growth process to start over," while the use of herbicides and pesticides favors monocultures instead of species diversity (Rains et al. 2011). Whereas these conventional systems remain at the base of the ecosystem growth curve and are dependent on continuous large external inputs (of water, fertilizers, pesticides, and animal feed), agricultural systems designed after the principles of mature ecological systems at the top of the growth curve are self-sustaining (Rains et al. 2011). In describing *Polyface* farm's strengths, Pollan says, "To measure the efficiency of such a complex system you need to count not only all the products it produces (meat, chicken, eggs) but also all the costs it eliminates: antibiotics, wormers, parasiticides, and fertilizers" (Pollan 2006). These costs include money (Pollan 2006), lowered environmental resilience (e.g., through fertilizer-based nutrient pollution; Foley et al. 2011) and negative effects on human health (e.g., via antibiotic-resistant genes spreading from bacteria infecting animals to bacteria infecting humans; Ling et al. 2013). Such an analysis of total costs (environmental, monetary, etc.) of a system "from cradle to grave" is the approach of *life-cycle assessment* (Arvanitoyannis et al. 2014). While agroecosystems provide inspiration, the viability of such approaches to make a significant global-scale contribution to feeding billions of people needs to be further validated.

Box 2. *Polyface* Farm's Mechanisms of Success: Intensive, Rotational Grazing, & Animal "Stacking." (Refer back to Fig. 3B).

The information below is drawn from Pollan's 2006 book The Omnivore's Dilemma.

It is one thing to write about the benefits of integrating ecological knowledge into the planning of agricultural systems and another to create a breathing example of such integration that can inspire others. Farmer Joe Salatin has done just that with his *Polyface* farm. Salatin's father William bought farmland that was badly eroded and, in some areas, had no remaining topsoil. William held a second job to support his family and read about grass farming (specifically, Viosin 1988), turned to composting instead of fertilizers, and began to invent contraptions to fit his vision for the future. Today, Joe Salatin successfully works the recovered, productive land full-time with the help of his children and interns, saying it is hard

> to believe that farming such a damaged landscape so intensively rather than just letting it be, could restore it to health and yield this beauty. This is not the environmentalist's standard prescription. But Polyface is proof that people can sometimes do more for the health of a place by cultivating it rather than by leaving it alone.

So, how does Salatin do it? His version of "intensive" farming is not the conventional version, but rather what he calls a "postindustrial enterprise," using new techniques.

Through use of moveable electric fences, Salatin raises his cows rotationally on pastureland using half-week intervals. By contrast, conventional grass-fed practice has animals graze continuously, resulting in fewer different types of grass surviving, with those that do being less productive and kept short with small roots that can only draw water and nutrients from the top layer of soil that consequently degenerates. Salatin's grasses are allowed time to recover, grow tall with large roots, and are then grazed back, encouraging the next growth cycle. Compared to continuously grazed pasture, Salatin's pasture produces more grass biomass and also new soil; the intermittently grazed grasses shed their long roots (to reduce their below-ground biomass when their above-ground biomass is consumed) that degenerate and form new soil.

Salatin not only raises healthy cows on healthy land but also produces pork, rabbit, chicken, eggs, and timber. His cows "mow" the grass for him, his chickens are then moved onto the pasture and happily pick at fly larvae growing in the cow manure, and in winter his pigs naturally facilitate the composting of a mixture of cow manure, woodchips, and fermenting corn (while rooting around in the mixture to find the corn). The animals Salatin has brought together fill different classic ecosystem roles they evolved to fill.

Pollan says "Most of the efficiencies in an industrial system are achieved through simplification: doing lots of the same thing over and over. In agriculture this usually means a monoculture of a single animal or crop." By contrast,

> Salatin's farm makes the case for a very different sort of efficiency – the one found in natural systems, with their coevolutionary relationships and reciprocal loops. For example, in nature there is no such thing as a waste problem, since one creature's waste becomes another creature's lunch. What could be more efficient than turning cow pies into eggs? Or running a half-dozen different production systems … over the same piece of ground every year?

Unlike crammed CAFOs of single-species, Salatin's farm relies on multiple animal species and their mobility to keep its system healthy. Mobility allows "stacking" of Salatin's animals on the same few acres, and is facilitated through inventions such as the electric fencing, a portable chicken coop, and his "shademobile" that gives his cows relief from the sun and that can be moved so that the cows follow it and evenly distribute their manure on the pasture as fertilizer without producing nutrient pollution.

Additionally, if Salatin were paying attention to economics alone, he would maximize production of chicken eggs as his most-profitable item, but he knows that "in a biological system you can never do just one thing, and I couldn't add many more chickens without messing up something else." Furthermore, his combined stacking method of raising multiple species actually provides an example that contradicts the idea that raising plant crops is always the most efficient way to produce calories: "researchers at the Land Institute have studied this question and calculated that in fact more nutrients are produced – protein and carbohydrate – in an acre of well-managed pasture than in an acre of field corn." Not every crop is equal, nor is every farm management style. Salatin and Pollan agree that farmers need to be willing to "practice complexity" as new way of thinking and designing their systems to require very few inputs, to be healthy, and to produce little waste. Working with the laws of nature instead of in ignorance of them or instead of fighting them can truly produce inspiring results.

As demonstrated by *Polyface* farm, (Box 2) and described by Kirschenmann (2010), agro-ecological approaches have demonstrated benefits such as:

> designs that feature complex, inventive, biological synergies within production systems wherein energy is exchanged among species and self-regulating and self-renewing, resilient, adaptive systems replace input-dependent, energy-intensive, control systems.

Adaptive management (see Introduction and Background Information) has arisen as a practice of resource and ecosystem management whose philosophy of working with principles of ecology and monitoring for changes in ecosystems can be applied to agro-ecological production of food. Because the "very nature of systems may change over time" (Folk et al. 2010), it is advisable to use diverse agricultural strategies that both cater specifically towards solving already understood problems (thus enhancing *specified resilience*) as well as maintaining biodiversity and various cultivation practices to enhance the chance that novel "shocks" can be dealt with (thus enhancing *general resilience* Folk et al. 2010). Growing traditional cultivars with higher resistance to biotic and abiotic stresses is a great example of enhancing both specific and general resilience in the context of climate change (see above), and multiple varieties should be raised to foster general resilience against, for example, potential novel emerging pathogens (Ebert 2014; see Newton et al. 2011). Elite cultivar monocultures present the opposite of species and genetic diversity and are thus more prone to abiotic stress challenges and pest and pathogenic epidemics (Newton et al. 2011), and present "ecological, nutritional, and economic risks" (Ebert 2014).

Just as CAFOs produce sick animals, the modern salmon industry has lost billions of dollars due to disease occurring in crowded fish pens (Bourne 2014a). Examples of aquacultural, or fish-farming, strategies are beginning to be sustainably applied to ocean farming; these farms link the areas of environmental resilience and human health by eliminating waste and producing nutritious food. Waste is eliminated through utilization of species that occupy different niches (e.g., clams and kelp filter fish waste out of the water), and nutritious food is produced by feeding the fish what they evolved to eat – such as the algae from which cold-water fish derive their healthful omega-3 fatty acids (Bourne 2014a). In the ocean and on land, real-world examples of models are thus becoming available that demonstrate the validity of basing agriculture on evolutionary and ecological principles. *Polyface* farm (Box 2) is not alone; Fairlie's farming model likewise "argues the case for the return to meat being produced from grazing by ruminants, and feeding crop and food waste to monogastrics such as pigs and chickens" (Wahlquist 2013).

Ruminant Methane Production and Nutrition

What about the concern that cattle produce the potent greenhouse gas methane? Both the nutritional quality of ruminant meat as well as methane-production levels have been shown to be highly variable and dependent on several factors, including the botanical diversity of the pasture (methane emission varied five-fold for different pasture plant species composition; Dawson et al. 2011) the cattle breed (Ricci et al. 2014), a cow's age at calving (Ricci et al. 2014; Wahlquist 2013), and the amount of milk produced (Ricci et al. 2014). A botanically diverse pasture (a polyculture with inclusion of non-grass species, such as clover; also used on *Polyface* farm) not only lowers methane emissions from grazing cattle but also improves meat nutritional quality (towards lower saturated fat and higher omega-3 fat levels; Dawson et al. 2011; Fig. 3B). Furthermore, in addition to the impact of pasture plant species, the particular grass variety used (with grass varieties differing in the ratio of cellulose to other carbohydrates and to protein) also affects methane emission rates of ruminant gut microbes (Kingston-Smith et al. 2010). As described in Wahlquist (2013), advocates of grain feeding point out that grain-supplemented cattle produce less methane per kilogram of meat due to their accelerated maturation process compared to most current grass-fed cattle. However, such analyses should be repeated for a comparison of grain-supplemented cattle with grass-fed cattle after incorporating all of the methane-emission-lowering suggestions summarized above.

The above findings allow recommendations on what grass variety, what pasture species composition, and what cattle breed and rearing approaches can be used to minimize methane production, while maximizing meat nutritional quality. Attractive local alternatives to cattle rearing have also been documented. Ruminants like goats and sheep can be raised under conditions unsuitable for cows, including steep or rocky landscapes (e.g., in Greece, Pomeroy et al. 2014) and, for the case of goats and donkeys, can subsist purely on tough, drought-resistant vegetation (e.g., during droughts in Kenya, McCabe 2008). Australia is native home to ruminant macropods such as kangaroos and wallabies. Grass-fed macropods produce 66-75% less methane (per weight unit of meat) than cattle as a result of the involvement of different gut microbes that produce mainly non-volatile byproducts (Wahlquist 2013) and, by being soft-footed, protect the fragile soils of their local environment (Wahlquist 2013).

It thus appears that solutions are already emerging for concomitantly maximizing food quantity and quality and minimizing environmental impacts like methane emissions. Dawson et al. (2011) likewise point to the “danger and inadequacy of considering each parameter in isolation” and advocate concomitant evaluation of multiple factors in a matrix that allows identification of solutions that optimize for all key goals together (see Fig. 4 below). The latter statement is in agreement with the conclusion of this chapter (Chapter 3) that concomitant optimization by more than one factor, such as human health (lowering the risk for human diseases and disorders) and the health of the physical environment (resilience), is not only desirable but also attainable. The next question is whether additional factors should be entered into the matrix for optimization, and if so, which factors should be added and by what criteria they should be chosen. While Dawson et al.'s (2011) matrix included two axes of (i) reduced methane emissions and (ii) meat quality; I have crafted my own matrix with three axes (Fig. 4).

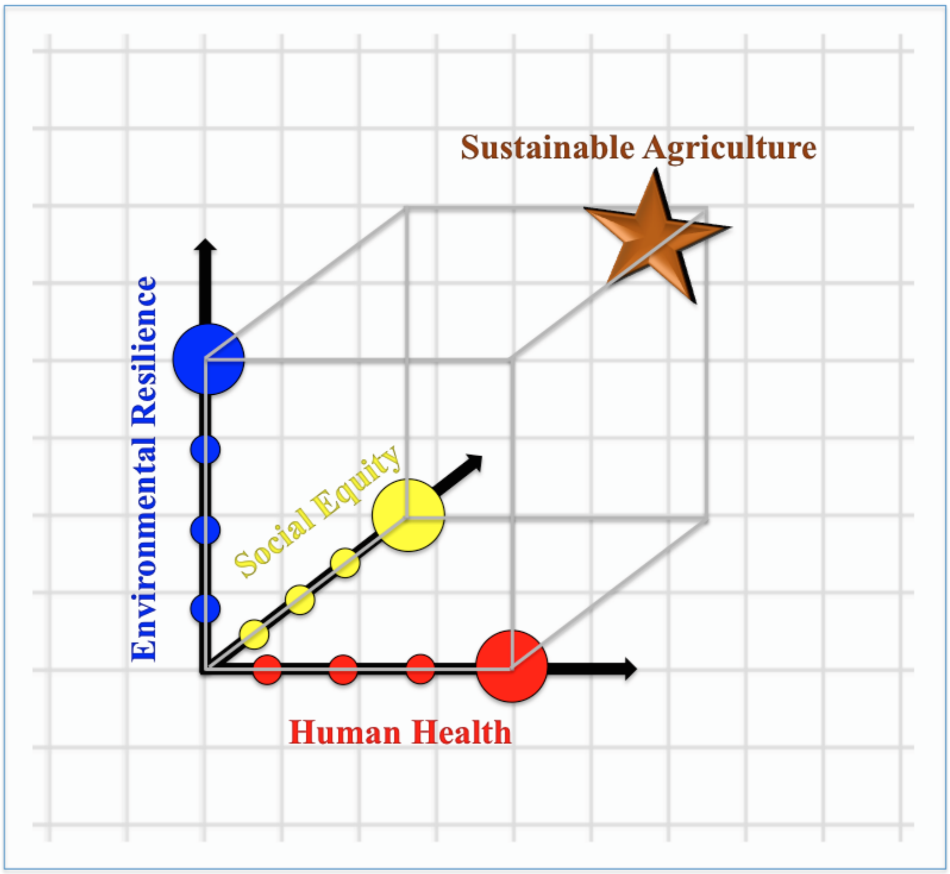

Figure 4. Three-dimensional matrix with three axes representing environmental resilience, human health, and social equity. The star symbolizes optimization of all three parameters for the outcome of sustainable agriculture.

Figure 4 depicts a three-dimensional matrix with the three axes representing the three key parameters to be co-optimized when constructing sustainable agricultural solutions: (i) environmental resilience, (ii) human health, and (iii) social equity. While independent maximization for only a single parameter leads to undesirable outcomes by leaving the other key needs unaddressed, multi-variable optimization of all three parameters in conjunction identifies truly sustainable solutions. At the same time, such an optimization approach allows single, or a few, optimal solutions to float to the surface, while dramatically reducing the often-dizzying array of alternatives that do not address all key parameters. While there is likely an optimal solution for a given place and time, sustainable solutions are expected to differ by local context, including variations in physical environment (habitat, see Chapter 1, and agricultural practices, see Chapter 3) as well as socioeconomic and geopolitical factors (see upcoming Chapter 4).

Indeed, one additional factor mentioned consistently by a number of the authors addressing human health and/or the health of the physical environment is social equity (one of the "three E's" of sustainably) – the challenge to serve not only a privileged human minority, but instead equitably serve all humans. In the latter context, the critical question remains: Can enough food be produced to feed the growing world population? As discussed in Chapter 1 above, Foley et al. (2011) predict that enough food can be produced *if* all interventions suggested by them (ranging from improved cropping efficiency on current agricultural land to reducing food waste) are "deployed simultaneously." It is important to note, as is also done by Foley et al. (2011), that not every proposed solution will work anywhere on the globe or will be adequate in every location. For food systems, from production to consumption, to be sustainable in their local context, local factors such as physical environment (habitat) as well as socioeconomic and geopolitical factors must be taken into account. Therefore, variability in food access, nutrition, and culture need to be taken into consideration to equitably meet the needs of people in an environmentally and culturally sustainable way.

Chapter 4
Consideration of Social Equity and Local Context

Social Equity as a Third Dimension of the Optimization Matrix

While there are already approximately 1 billion people going hungry today (Foley et al. 2011), there will be an additional 2 billion mouths by 2050 due to the growing world population (Foley 2014; Kahane et al. 2013; Ruiz et al. 2014). Reasons for including social equity among the key factors for co-optimization include moral arguments as well as the argument that serving the world community as a whole is a prerequisite for long-term sustainability in a political and societal sense. Conversely, political and societal stability are required to attain long-term sustainability of human physical and mental wellness and of the physical environment. For example, it may be difficult to motivate investment in rebuilding soil fertility and resilience if people "fear being uprooted" due to political instability (Vince 2010). For these reasons, I will add social environment as a third factor (Fig. 5) for inclusion in a matrix for multi-variable optimization (see Fig. 4).

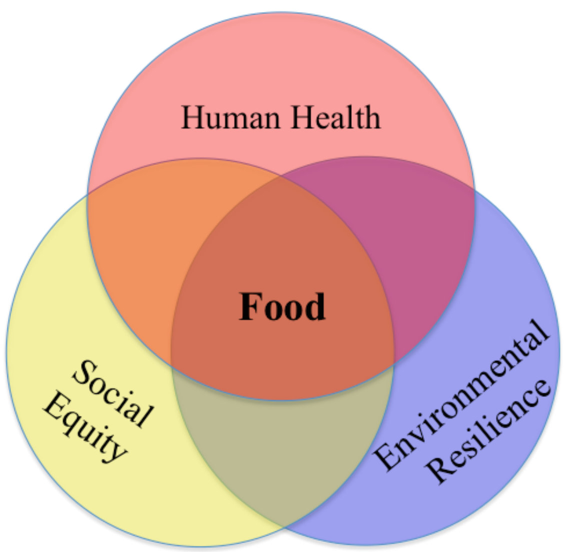

Figure 5. Schematic depiction of food at the intersection among human health, environmental resilience, and social equity.

This reasoning broadens the concept of sustainability as used in this thesis beyond the nutritional quality and total quantity of food produced on the planet (as well as access to other physical resources) to include *access* to food of enough quality and quantity for more people. Access controls the food choices individuals can make, and this access is based on many *institutional* factors beyond the immediate control of the individual. As further elaborated below, these factors include allocation of land to crop versus meat production, global trade of food, global food market prices, the balance of small and big farms, food waste, agricultural subsidies, and wages. Simopoulos et al. (2011) explain that the term "diseases of life-style…emphasizes individual rather than institutional responsibilities for avoiding disease, but in all cases the responsibility for promoting health is obviously dual." The same goes for environmental health. In order to truly address issues of sustainability, research from the natural and social sciences (including institutional-level socioeconomic and geopolitical analysis) will need to be integrated (Reid et al. 2010).

Chapter 2 led to the identification of just a handful of essential nutritional requirements for human physical and mental health – and to the conclusion that a traditional Mediterranean diet meets these nutritional requirements and has already been shown to dramatically reduce the risk of physical and mental disease. However, not all regions of the world can support production of the specific foods that make up the Mediterranean diet, nor would there be cultural acceptance of a single diet around the globe. The mandate of social equity demands attention to local circumstance and culture. Fortunately, the identification of the handful of essential nutritional requirements for human wellness (Fig. 2, i.e., a low glycemic load, low saturated fat, a balanced omega-3 to omega-6 fatty acid ratio and ample antioxidant minerals and vitamins), offers a generic formula that can be met by a wide variety of diets with different combinations of plant-based foods versus meat as well as different proportions of the macronutrients of carbohydrates, protein, and fats – as long as fats are predominantly unsaturated and balanced in their fatty acid ratio and as long as the carbohydrates are slow-burning. Humans have long been masters at occupying just about every type of ecosystem by making use of the local available food resources (Gibbons 2014).

As detailed in Chapter 1 and stated again above, Foley et al. (2011) conclude that a doubling or tripling of global food supply is achievable by implementation of a wide range of agricultural approaches and appropriate technologies optimized for local conditions of climate and other factors, and by reducing the current rampant post-harvest waste of food on a global scale. Together, Foley et al. (2011) and Foley (2014) also suggest that the current polarization of the debate of, for example, meat versus no-meat, GMO versus no-GMO, and small- versus large-scale farming (all touched on below), must be overcome to craft local solutions in an ideology-free context from all available options that can contribute towards sustainability and social equity. This call for integration of all possible solutions is echoed by Lichtfouse (2010) who presents a summary of 100 recent agricultural reviews on various available solutions that could contribute to societal sustainability. The following sub-sections will briefly consider the major topics in Chapters 1-3 in the context of social equity as well as consider additional institutional factors that can either limit or increase access to food.

Meat Versus Plant-Based Foods in the Context of Social Equity

Even though meat production is more resource-intensive and less calorically efficient than plant-based food, meat is nevertheless essential in those vast land areas that cannot support crop production (see Chapter 1). Furthermore, animal manure (from ruminants and non-ruminants alike) plays a key role in nutrient recycling that contributes to fertile soils (Flachowsky et al. 2013, see also Box 2). Careful consideration needs to be given to the specifics of meat production and consumption, both of which should be tailored to location with respect to physical and societal factors. Humans as omnivores possess the ability to thrive on a wide diversity of different diets, ranging from mostly plant-based diets to mostly meat-based diets (groups such as the Inuit obtain vital vitamins such as vitamin C from blood and raw meat; Fediuk et al. 2002). Meat is, in fact, a critical dietary source of protein and mineral nutrients, especially in developing countries (Capper 2013) where meat consumption is currently low but rising. At present, 15% of the world's meat is consumed by the U.S. population that represents only 4.5% of the world population (Stokstad 2010). Many argue that meat consumption should only be lowered in developed countries, and should be allowed to rise elsewhere (Capper 2013; Wahlquist 2013). Others warn that appropriate attention should be paid to possible ensuing fluctuations in market prices of meat and non-meat foods as a possible result of a lowering of meat consumption in the developed countries (Stokstad 2010). While some individuals in the developed world are becoming vegetarians for environmental reasons or ethical reasons related to animal treatment, it appears that, to serve all humans on this planet, meat production will have to remain part of the global food equation. Prominent moral philosopher Peter Singer (author of *Animal Liberation*, 1975) recently agreed with Michael Pollan (2006), who concluded, "What's wrong with eating animals is the [conventional] practice, not the principle" and, while condemning inhumane slaughterhouse practices as inexcusable, observes that farms like *Polyface* give their animals a happy life (Pollan 2006; for more detail on ethical reasoning, see Pollan's Chapter 17). Neither meat production nor consumption should be maximized, but should rather be optimized in an ethical manner to meet local environmental parameters and nutritional needs (such as described in Chapter 3).

Vegetables Versus Grains in the Context of Social Equity

The analysis of worldwide crop production by Foley et al. (2011) notably focuses on 16 "major crops: barley, cassava, groundnut, maize, millet, potato, oil palm, rapeseed, rice, rye, sorghum, soybean, sugar beet, sugarcane, sunflower and wheat," a list including many grains and notably few vegetables (compare Bourne 2014b list). Since the beginning of agriculture as "the foundation of society" (Lichtfouse 2010), grains have provided "calorically productive starches that could be obtained in large quantities per unit of space and then stored" (Cohen 2003). On the other hand, grains and the beginnings of agriculture have also been associated with a reduction in the diversity of human diets (Gibbons 2014) and with "diseases of civilization" such as cavities (Cohen 2003; Gibbons 2014), arthritis, bone lesions (Goodman and Armelagos 1985), heart disease, diabetes, and others (Eaton and Konner 1985). What motivates the continued production of grains today? Are the reasons purely habitual or economic, or can the growing of grain crops today be justified from an environmental, human-health, or social equity perspective?

Single foods alone can hardly ever provide all of the nutrition required by humans (e.g., corn-based diets do not provide several essential amino acids, including lysine; Goodman and Armelagos 1985); most foods need to be eaten as part of a diverse diet. Grains can, in fact, be part of a healthful diet – the Mediterranean diet does include grains along with vegetables and fruit as well as some meat. The ancient "Mediterranean triad" consisted of grains such as wheat and barley, olives (often consumed as olive oil), and grapes (often consumed as wine), and was eaten with spices, vegetables, fruits, legumes, nuts, and fish, as well as goat and sheep meat and cheese (Pomeroy et al. 2014). These foods supported, for example, Ancient Greece because they were perfectly suited to growing in the local climatic conditions (Pomeroy et al. 2014). Remaining traditional Mediterranean diets today are remarkably similar, and are low in free sugars, low in saturated fat, and rich in omega-3 fats (from fish, nuts, etc.) and antioxidants.

Before humans started settling down and cultivating crops, hunter-gatherer societies usually had population densities below "ten persons per 100 square miles" (Pelto and Pelto 1983). In order to feed current and future human populations worldwide and support social equity and food security (the fact that grains can be stored throughout the year is still an important bonus today, as it was in ancient times), grain may need to remain part of a healthful diet. Just as vast rangeland areas are best suited for meat production, other areas can be best suited for grain and cereal production as opposed to the growing of other types of crops that require more water. Unlike most vegetables, many grain-producing species can be grown under dryland agriculture (i.e. without irrigation) (Dorminey 2012; Hansen et al. 2012). For some arid areas, rotating grains with nitrogen-fixing legumes has been recommended to avoid nitrogen-depletion of soils (Jan et al. 2013). Furthermore, some traditional grains, such as quinoa, can be grown in conditions of poor soil, low water, and high salinity (Ruiz et al. 2014) and exhibit less unbalanced omega-3 to omega-6 ratios than widely used modern grain species (Park and Morita 2004).

Lastly, and just as is the case with meat production, it may not be the principle of grain production and consumption of unrefined, whole-grain that is problematic from a human-health perspective, but rather the processing into white flour (Tiwari and Cummins 2009; Van Hung et al. 2009) and the current subsidization of mass production of a few grain varieties lacking in both hardiness and nutritional quality (see Ruiz et al. 2014) at the expense of vegetable production

(McMillan 2014). Therefore, subsidies should be shifted and grain production should focus on species (such as quinoa, Ruiz et al. 2014), varieties, cultivation conditions, and processing methods that optimize (i) grain nutritional quality for humans and (ii) ability to thrive under local environmental and climatic conditions with minimal external input of water, fertilizers, and pesticides, and (iii) rewarding the stewardship of traditional grain species and varieties by native people (Ruiz et al. 2014).

Globalization, Dietary Delocalization, and Dietary Diversity

Jacka et al. (2014) conclude that "the opening of trade markets to global partners and the shift from local production and distribution of food to transnational corporations" have played important roles in an increase of diet-related chronic diseases worldwide. New worldwide availability of processed foods is indeed at the center of the nutrition transition (see Chapter 1). While the trade of food may have increased the dietary diversity (as range of foods eaten) of certain populations, especially in developed countries, dietary diversity has often been reduced in certain regions of developing countries (Pelto and Pelto 1983). Reduced dietary diversity is experienced in regions where local subsistence strategies are replaced by the production of a single food for export, and the money earned is used to buy imported processed foods of poor nutritional quality (Pelto and Pelto 1983; see also Miskito Indian green turtle case study in Nietschmann 1974). Pelto and Pelto (1983) coined the term "dietary delocalization" to denote the increasing global trend towards non-local food sources. Export of food can bring in much-needed monetary support (Bourne 2014b), but reliance on imported staples can also expose already vulnerable communities to fluctuations in world food prices (as occurred recently due to a spike in the cost of fossil fuels and other agricultural inputs as well as increased biofuel production; Raudsepp-Hearne et al. 2010; see also Lichtfouse 2010 on the "globalization of the market for food"). In addition to the health detriments of modern diets, "greater homogeneity in world diets… makes the food supply more vulnerable" (Gibbons 2014) to sudden change (see Chapter 3 discussion of resilience and diversification of agriculture). Agricultural biodiversity (and the related dietary diversity) via local production of varied foods has thus been suggested to foster both environmental and human health (see e.g. Kahane et al. 2013 and Wahlqvist 2014).

One might conclude that each region should put thought into what ratio of reliance on local to non-local foods would be optimal for reaching food security now and over the long-term, as well as, from the environmental perspective, a small carbon footprint via reduced fuel expenditure for food transport (Reijnders and Soret 2003). There is, however, no one-fits-all answer (Lichtfouse 2010). Lichtfouse (2010) argues that "Scientists and policy makers should therefore study, assess, and enforce the relevant level of goods circulation" and that "the poorest nations should be at the same time supplied with food and helped to produce their own food and energy." The same author also argues that, in most cases, a lesser dependence on imported food sources would be to the "environmental, social, and security" benefit of nations (Lichtfouse 2010), aligning with the concept of resilience (see Introduction and Background Information; Chapter 3). On the other hand, some trade of food may help developing countries avoid the large, uneven burden of global warming upon food production predicted to be felt disproportionately in the southern latitudes (Newton et al. 2011). Concerning the role of large agribusinesses, models have been proposed for the *coexistence* of small farms for production of local food, with large-scale agricultural systems that produce exports; for example, in Mozambique small farms serve "as a safety net and source of pride" while large farms bring in funds for infrastructure and contribute to global food production (Bourne 2014b). Once again, it appears that the specifics of implementation and local context are key to whether or not large corporations can play a constructive role in sustainable food production.

When it comes to the exchange of food and crop seeds, promising existing, locally-maintained traditional crop varieties (landraces) should be considered for adoption in equivalent climate zones elsewhere. As pointed out by Ruiz et al. (2014), it is often local native populations of people who have preserved traditional food sources, such as quinoa, that may offer solutions as crops with not only superior hardiness (with respect to drought, salinity, and pest resistance) but also superior nutritional quality (with respect to macro- and micronutrient composition). Ruiz et al. (2014) end their paper by saying quinoa is currently "underutilized" but "could become a major crop," and ask how to ensure that the Andean farmers who contributed to the conservation and breeding of this crop are among the beneficiaries of a more widespread utilization of this crop. In the end, when considering sustainability from a social equity perspective, it is of great importance whether or not local communities are able to meet their nutritional needs and profit from their heritage foods and exports. In the future, exploitative harvesting of wild foods from regions (such as river algae from the Lao People's Democratic Republic; Esterik 2006) that depend on these foods should be avoided. For example, the appeal of exotic foods flown in from far away may often be misplaced, and local foods can often meet nutritional needs in a sustainable manner. A number of studies have shown that local varieties of vegetables and spices have a higher nutritional quality with respect to antioxidants than the few elite varieties that dominate the modern Western diet (see Chapter 3; see Ninfali et al. 2005 for 27 vegetables, 15 aromatic herbs and some spices from Central Italy; Rop et al. 2011 for native apple cultivars from Central Europe; Rop et al. 2012 for edible flowers; Morales et al. 2014 for non-cultivated vegetables, or "weeds," traditionally consumed in Spain).

The number of suggestions of novel food production for broad human consumption is growing and includes algae (Christaki et al. 2011), krill (Tou et al. 2007), or insects (see Dufour 1987 for traditional dietary roles and nutritional benefits of insects), as non-exploitative and nutritious options to help feed the world population. These suggestions – along with all current options – should be evaluated for their potential of fostering a healthy environment, healthy people, and a healthy world society. As stated by Foley et al. (2014), humanity cannot afford to shun any options that meet the latter criteria.

Transgenic Crops

Foley et al. (2011) recommend not excluding genetically engineered, or transgenic, crops from the array of options for sustainable food production that can meet the world's consumption needs. While Foley et al. (2011) support the inclusion of transgenic crops to feed the world population (equity) and from an environmental perspective, I will additionally present evidence that genetically engineered crops also should not be ruled out from a human-health perspective. Transgenic crops contain a gene from another organism that can, for example, offer increased yield, nutritional value and resistance to abiotic and biotic stresses (Christou and Twyman 2004), a reduction of need for pesticide application, and more (see full list at PG Economics 2014). Over the past decades, concerns were raised about possible negative health impacts of human consumption of transgenic crops, such as fear of allergies caused by transgenic foods in the human consumer (DeFrancesco 2013), and about the risk of spreading the engineered gene to wild relatives of crop species (Mlynárová et al. 2006; Moon et al. 2010). Since then, these concerns have been alleviated by excision of the transgene before plant reproduction (thus preventing the spreading of the gene to other crops; Mlynárová et al 2006; Moon et al. 2010) as well as by the implementation of tests that ensure that the added proteins are destroyed by human stomach acidity and thus cannot cause allergies (DeFrancesco 2013). It is prudent to evaluate all new technologies for their safety from both environmental *and* health perspectives, and activism surrounding the issue of transgenic organisms may have played an important role in causing the above-listed concerns to be addressed. However, current activism that targets transgenic organisms frequently focuses on unfounded claims. This opposition fails to acknowledge the promise of transgenic organisms to, for example, reduce pesticide use (PG Economics 2014). This opposition also detracts from concerns of social equity, such as who holds intellectual-property patents, who is in control of decision making and regulations, and who profits from transgenic crops (Herring 2007). It appears that, just as is the case for the debate over meat, or grains, the validity of transgenic crops will depend on how they are implemented and whether local people are culturally accepting of the technology and are among its beneficiaries. Some authors have suggested that developing countries may derive the greatest benefits from the cultivation of certain transgenic crops (Christou and Twyman 2004; Farre et al. 2010; PG Economics 2014) while other authors express doubts (for both sides of the debate see Herring 2007).

Food Waste

How food is produced is a focus of the present thesis – as part of a new and necessary larger conversation of how to sustainably provide nutritious food and food security for a population rapidly approaching 9 billion. Chapter 4 has brought in discussion of the larger regional and global food systems. However, cutting the rampant waste of currently available food is also critical. As reported by Foley et al. (2011),

> Developing countries lose more than 40% of food post-harvest or during processing because of storage and transport conditions. Industrialized countries have lower producer losses, but at the retail or consumer level more than 40% of food may be wasted.

Reducing food waste is a huge but promising task that would lessen the environmental burden of agriculture and improve human health by increasing equitable access to food; Foley et al. (2011) recommend beginning by reducing the waste of foods that take the most energy to produce, i.e., meat and dairy. Additionally, as examined next, access to food is not only an issue in developing regions that lack infrastructure such as adequate roads and refrigeration technologies, but also in the wealthiest country on Earth.

Food Access: Poverty and Diet

Schoenthaler and Bier's studies (Schoenthaler and Bier 2000; Schoenthaler et al. 2000) that found striking effects of even minimal nutrient intervention, in lowering antisocial and violent behavior and raising academic performance, was conducted in two working class schools in Arizona with predominantly minority students; this may be an important context in which these startling results should be evaluated. It has been shown that not everyone in the United States is eating the same diet – and that there is a growing *diet gap* along class lines between the United States' rich and poor (Wang et al. 2014). Since the late 1990s, there has been a 57% increase in *food insecure* households (that regularly run out of food) in the U.S., now reaching 48 million families, of which more than half are white (McMillan 2014). While many factors contribute to growing hunger and dependence on fast food in the U.S., these factors generally fall under the overarching issue of poverty stemming from low wages that cannot properly support families (McMillan 2014). Poverty and inequity are the reason for (i) the existence of *food deserts* – housing areas more than half a mile from the nearest grocery store, with residents who cannot afford a car and thus do not have access to fresh foods, (ii) a lack of knowledge and time to make inexpensive healthy meals at home (especially for families working multiple jobs around the clock), and (iii) dependence on cheap, highly processed, and nutritionally imbalanced foods. These foods are cheap due to subsidies concentrated on “a few staple crops” (corn, wheat, soybeans) used to make processed foods, such as cheap sodas made with corn syrup (McMillan 2014). Subsidies should be redirected to support the availability of non-processed foods.

The *National Geographic* article by McMillan (August 2014) states that, “The root problem is the lack of jobs that pay wages a family can live on, so food assistance has become the government’s – and society’s – way to supplement low wages.” The foods that are part of the 75-million-dollar food-assistance program (which only comes to $1.50 assistance per meal) are predominantly “high in salt, sugar, and fat;” thus, even a hungry family who skips meals can be overweight (McMillan 2014; see also Chapter 2 Fig. 2). Instead of providing an ounce of prevention through paying employees living wages, the current system provides a pound of purported cure through food assistance (which, however, ironically creates its own problems) and the world’s most expensive health care system (Edney 2014; Gimein 2014). The current system denies the American lower class a living wage and relies on taxes to provide minimal social services that rack up huge monetary, social, and health tolls, and cannot even begin to address, for example, those cases of violence that may be linked to malnutrition. While the scientific results are in (albeit at varying levels of press coverage – I have not seen Schoenthaler and Bier’s 2000 study in the news), perhaps not everyone is comfortable with accepting these results. It may be painful to accept responsibility for previous and future outcomes as huge as the health of one’s family or fellow citizens. The road to fixing the problem starts with realistically acknowledging the problem’s causes, whereas ignoring such information could be considered a true lack of freedom of choice. Existing limitations to food access must be addressed to reach social equity, and access to nutritious food (as the basis for health, academic achievement, and full participation in society) should be seen as part of the constitutional mandate for equal opportunity.

The issue of poverty restricting access to food applies across the globe. Foley et al. (2011) attribute the currently undernourished population of 1 billion predominantly to "continued poverty and mounting food prices," with food prices increasing due to rising fuel costs, climate change, and allocation of crops to bioenergy (Lichtfouse 2010; Raudsepp-Hearne et al. 2010; Foley et al. 2011). Poverty can also restrict agricultural *production* – Africa has the largest *yield gap* between potential yield and actual production due to "poverty, civil unrest, and a lack of access to credit" (Bourne 2014b). Poverty often leads to a poor diet, which, in turn, lowers work capacity and hinders economic growth on a personal and societal level (Bender and Dufour 2012). However, as discussed throughout this thesis, poor diet is not only a characteristic of the poor. Restrictions to the ability to reach full physical and mental capacity apply to all who eat a poor diet, whether due to poverty or simply to reliance on a Western diet. The spreading global epidemic of chronic diseases and disorders must be addressed, and can be ameliorated at the same time as environmental resilience is fostered.

Summary & Concluding Remarks: It's All in the Framework

> In spite of…close relationships between agriculture and food production on the one hand and nutritional and ecological problems on the other, policies for agriculture, for the environment and for human nutrition and health are largely disconnected. In our analyses, priorities and policies, we quite obviously need to take a broader view, one that at the very least recognizes the complex relationships between farming, human health, and the ecological systems on which life on earth depends (Simopoulos et al. 2011).

While few existing documents explicitly call for or demonstrate these connections, there is recognition of the need for interdisciplinary and coordinated research, from both developed and developing countries (Leiserowitz et al. 2006), and dissemination of this knowledge (e.g., see global change funding agencies discussion under the Belmont Forum, Reid et al. 2010). In its own way, this thesis responds to the call of these pioneers and aims to equip the reader with compelling and mechanistic-level examples of connections in these areas. In response to the questions raised in this thesis' Introduction and Background Information section, I conclude that many of the stories we hear on the news are indeed less disconnected than they may seem, and that agriculture and food are at the center of human society's challenges in the 21st century. In particular, my hypothesis was tested and confirmed, revealing that there are indeed existing and emerging models for revised food production systems that can simultaneously ameliorate environmental degradation and loss of resilience and the global burden of chronic human disease and disorder. In the past, society has successfully addressed single-factorial environmental problems that were easy to visualize and target: removal of lead from paint (EPA Lead 2014), banishment of CFCs (chlorofluorocarbons) to protect the ozone layer (EPA Air 2014), and legislation banning trans fats in Denmark, California, and New York City (Brownell and Pomeranz 2014). My thesis highlights the salient key issues underlying the multifactorial links among the complex challenges of the 21st century. As will be elaborated further below, subsequent to a summary of the key messages, my thesis aims to provide further motivation for public engagement with multifactorial issues by demonstrating several unanticipated rewards of such an undertaking.

Throughout this thesis, the various links and feedback loops depicted in Figure 1 have been supported with detailed evidence. Environmental resilience is linked to current human-health concerns through food quality determining the global risk for human diseases and disorders. Food quality depends on environmental resilience as a factor that also secures food quantity. Environmental resilience is linked to future concerns of global reductions in food quantity that would threaten human society. At the same time, it is important to note that low food availability to individuals (most often due to poverty) is already prevalent in certain areas and communities, taking into account the approximately 1 billion people who are hungry today.

As detailed in Chapter 1, conventional agriculture relies on high inputs (fuel, water, fertilizers, pesticides, antibiotics, animal feed, etc.) and creates pollution. Agricultural productivity gains are presently slowing and agriculture itself changes the environment (e.g., through climate change and degradation of land and water) in ways that have already begun to threaten local food production. There is, thus, a *future* prediction of continued and amplified diminishing returns on investment when it comes to global food yields (Fig. 1). But human life quality *today* is already diminished due to food-related human-health problems (Fig. 1). As explained in Chapter 2, both developed and developing countries are experiencing high occurrences of chronic human diseases and disorders associated with progression along the nutrition and epidemiological transitions. This rising global epidemic incurs high costs in terms of human suffering and economic losses, and can be traced back to lifestyle and environmental factors with a heavy influence of diet (Fig. 2). Bringing in a nutritional focus, as done in this thesis, does not simply add human-health status to the list of contemporary problems, but instead highlights mechanistic connections between environmental and nutritional human-health issues. While protecting the ability to produce enough food quantity may be the ultimate concern in light of population growth, a better understanding of the fundamental connections between present and future problems (Fig. 1) should help to reach those who are unconcerned by future threats to the food supply when they see fully-stocked grocery stores. Instead, food-related issues that affect everyday lives – the health problems of family members today – should be used to solicit a response. Moreover, while all chronic human health conditions share the same underlying dietary causes (Fig. 2), people may be more likely to respond to education about learning and mood disorders (e.g., depression, ADHD, violent behavior, etc.) and physical fitness (e.g., how to look one's best and "avoid flab") that affect individuals of all ages, rather than about chronic diseases that strike later in life (e.g., heart disease, cancer, Alzheimer's) (Jacka et al. 2014). We need a veritable revolution now in public engagement with environmental issues, but the sustainability movement has not garnered enough support, presumably due to its complexity, lack of imagery (Leiserowitz 2006), lack of immediacy in time (Raudsepp-Hearne et al. 2010), and an unclear connection to personal impact on one's own family (see Introduction and Background Information section). Equipped with knowledge of mechanistic connections and available solutions, people should have no reason not to act, no matter what angle they care about – environment, health, economy, social equity, or others.

Mechanistic-level analysis holds explanatory and predictive power that creates opportunities for manipulation of outcomes through policy making. As reviewed in Chapter 2, dietary nutrients provide building blocks required in the human body for brain and other tissues, such as the structure and function of the sodium-potassium pump required for generating the precondition for nerve impulses as the basis of human thinking (Box 1). I have also shown that dietary nutrients play a role in regulating vital human genes, with excess consumption of saturated fat and sugars causing accumulation of visceral obesity that is linked to immune system dysfunction and low-grade chronic inflammation that contribute to all of today's chronic diseases and disorders (Fig. 2). There is a need to make sure that "the general public, clinicians and policy makers are aware of the links between dietary behaviours and mental health" and chronic disease (Jacka et al. 2014) – it is vital to realize that these health conditions are highly preventable and not inevitable, even if disease and disorder have become the norm in today's society and may run in one's family, often attributable to epigenetics and lifestyle factors. Jacka et al. (2014) say,

> [B]ecause of the scale of the burden of illness…and the universality of food as a modifiable risk factor, the benefits of even small improvements in the food environment, leading to improved dietary intakes, may translate to large gains in mental health at a population level.

Small policy adjustments promise large potential societal gains (see also Foley et al. 2011 as described in Chapter 1 for a few key policies to sustainably increase global food production). From both an environmental perspective and a human-health perspective, conventional food production systems should be revised by incorporating approaches that concomitantly optimize for both sustainability and nutrition – as there are costs to keeping this analysis disjointed.

While the multifactorial thinking called for above should be fostered through education, the education system can, in turn, expect to benefit from improved nutrition that has been shown to bolster students' school performance and learning and decrease symptoms of learning disorders (see Chapter 2). Specifically, students should be offered opportunities to explore complex issues and to practice critical-thinking skills that enable consideration of multiple factors. The benefit of addressing challenging issues via multifactorial, holistic analysis may, in fact, include a more optimistic viewpoint of these daunting issues. When the array of issues that face humanity in the 21st century are examined in isolation – one variable at a time – a dizzying number of competing problems and possible actions may cause individuals to opt for denial and inaction. In contrast, examining several issues via a multifactorial matrix (see Fig. 4) may allow single approaches to unequivocally emerge as the best solutions for a given local context and time, which should provide direction and motivation for action and improve stakeholders' morale and engagement. Addressing agricultural-production-system design from a combined environmental and human-health perspective allows novel insights to be gleaned and compatibilities to be identified. It is my hope that the present thesis has helped to provide reasons for optimism and has outlined some manageable avenues towards a sustainable future for humanity.

As summarized in Chapter 3 (see Fig. 3B), food crops and crop-growing techniques are already available that enhance environmental hardiness, increase nutritional quality, and boost the yields of plants (from, e.g., crosses of elite cultivars with traditional cultivars, crops raised without excess water, etc.). Furthermore, there are sustainable livestock-rearing options that make use of otherwise unproductive lands (via rotationally intensive grazing of ruminants), provide balanced human nutrition (by feeding the animals what they have evolved to eat), lower ruminant methane emissions (through pasture species diversity), and produce minimal waste (when animals are raised together and fill the respective waste-recycling roles of natural ecosystems; see Chapter 3, including Fig. 3B and Box 2). As opposed to conventional reliance on CAFOs and monocultures of elite cultivars, designing agricultural systems with the features of mature natural ecosystems promises to render agricultural systems self-sustaining and requiring fewer inputs (Rains et al. 2011; Chapter 3). Furthermore, making the recent breakthroughs in the understanding of the strong mechanistic interdependence among all living organisms (including humans) and the physical environment on this planet a topic of educational curricula should help disseminate the understanding that holistically protecting the Earth's ecosystems benefits individuals, their communities, and the world (as three different societal levels often presumed to benefit from separate actions; Costaza 2000).

As outlined in Chapters 3 and 4, there is frequently more than one possible solution, and which is optimal depends on local contexts. This context can include the confluence of different factors, including the local physical environment (habitat) as well as socioeconomic and geopolitical factors. Such an integration of social equity and the variety of local contexts (see Chapter 4) could potentially cause a multiplication of options at the global level, but can also lead to the emergence of only one or a handful of solutions that meet all stipulations (compare 3-axes of Fig. 4). Policies should be based on a small set of principal factors required for human health and a sustainable physical and societal environment. Concerning diet (see Chapter 2 and further discussion in Chapter 4), any diet providing balanced macronutrients, a balanced omega-6 to omega-3 fat ratio, and ample antioxidants promises to provide the same health benefits as the Mediterranean diet. Similarly, any ecosystem in which all essential functions are fulfilled will be sustainable irrespective of what specific species fulfill these respective roles (e.g., Chapter 3 Box 2). Therefore, the response to the question of whether we, as a global community, should cultivate grains, raise ruminants, grow local underutilized plants, and trade with each other when appropriate, is "YES."

As summarized in Chapter 4, there is a place and time for any and all approaches able to meet the criteria of supporting human health, environmental health, and social equity. In other words, a single solution for all local contexts is neither feasible nor desirable, as the solution for one location might not work in another location, and as today's solutions might not work tomorrow. Adaptive management (as defined in the Introduction and Background Information section) applied to a diversity of strategies and organisms should bolster both ecosystem and social *resilience* (i.e., both specific and general resilience, Chapter 3). As stated above, sustainability is not about *maximization* of any one factor, but about *optimization* of a small number of key factors (see Fig. 4) that may vary by location and context. Moreover, including social equity among the key factors for optimization (as done in Chapter 4) broadens the concept of sustainability in the context of the food supply beyond the nutritional quality and total quantity of food produced on the planet to include access to food of enough quality and quantity for more people. Of increasing importance are the goals to sustainably produce, and provide access to, enough nutritious food via policy changes to institutional factors, such as exploitative trade, subsidization of low-quality foods, and low wages, that negatively restrict individual choice (see Chapter 4).

From Food to Food for Thought

This thesis set out to examine how to motivate broad public support for action on environmental issues by highlighting the link between environmental degradation and chronic human diseases and disorders rampant today. The evaluation of these links, however, outlines not only evasive action to avoid future threats to global food security, but also outlines opportunities for unanticipated gains in human wellness – based on a novel understanding of the evolution of environmental regulation of vital human gene-regulatory networks. Again, rather than viewing such evolved dependencies as constraining human freedom, these can instead be viewed as opening the door to wholly unanticipated opportunities for humankind.

Humans respond strongly to cues from their environment – including food – via genetically programmed physiological responses that evolved to increase survival and reproductive success under conditions of changing food supply (see Chapter 2). "Advances" in modern agricultural practices, resulting in excess consumption of sugars and saturated fat, along with deficiencies in antioxidants and omega-3 fats, were made before the discovery of the principles linking human physiology to the environment, and inadvertently created adverse health outcomes (see Chapter 2). Multiple different food acquisition systems used by humans – hunter-gatherer strategies, early agricultural, and conventional agricultural practices – each feature unique strengths and weaknesses. Humanity now has the opportunity to design food production systems based on a deep understanding of evolution and ecology to achieve levels of human wellness that have never before been attainable. Growing our crops and raising our food animals with post-modern technology (see Box 2) according to the principles under which these organisms evolved will ensure not only their health but also that of the human consumer. On the basis of the links summarized in Chapters 2 and 3, one can imagine a world where diseases are uncommon and where food security, astute mental acuity and physical wellness are the norm – as fostered by a few synergistically acting modifications in our food systems.

In conclusion, humanity today has more in-depth knowledge than ever before to decide its own fate: "global society today has the opportunity, emerging knowledge, and resources to consciously create the future it desires" (Leiserowitz et al. 2006). A revised definition of sustainability should thus focus less on averting future disasters and more on creating healthy systems today; in fact, the very concept of sustainability can be argued to be synonymous with the concept of health. Furthermore, health in one area is inseparable from health in another; a healthy environment begets healthy agriculture and healthy people, healthy culture and society, and healthy economy. Such a viewpoint prompts a move away from special-interest concerns (as invited by Schellenberger and Nordhaus 2004, as cited in the Introduction) to consideration of all of the latter issues as intricately connected. The quest for sustainability will therefore not halt progress, but will instead offer opportunities never before imagined. Sustainability thereby becomes the method to achieve progress, rather than being the end-goal of it.

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