This article was published with a few revisions in:
***Int. J. of Thermal & Environmental Engineering*, Volume 4, No. 2 (2012) pp. 149-156**

AN OPINION PIECE

Overview of the Roles of Energy and Water in addressing Global Food Security

John R. Hillman, 11 The Logan, Liff, Dundee, DD2 5PJ, UK
Elias Baydoun, American University of Beirut, Beirut, Lebanon

ABSTRACT

Agriculture is mankind's greatest achievement enabling the advancement of civilisation and the development of settlements and communities. Specialisation in various types of agriculture coupled to using energy and products derived from fossil fuels have facilitated food production to keep pace with the dramatic rise in population. Global food security in the modern era is inextricably linked with security of water and fossil-fuel-derived energy supplies. The scale of the challenge to ensure adequate food supplies for an expanding global population in an era termed the Anthropocene, where human activity is leading to marked climate change, rapid urbanisation, modification of the natural environment, and pollution, will drive new forms of agricultural and horticultural practice because much of the global food system is not sustainable. Of necessity, it will involve enlightened governmental policies in addition to a lessening of fossil-fuel dependency, enhanced water-use and nutrient-use efficiency, new forms of cultivation and processing, efficient farming businesses, and greatly improved crop and livestock breeding. Farming the seas and oceans will be inevitable.

Keywords: Food security, agriculture, horticulture, water, energy, sustainability

GLOBAL FOOD SECURITY

Food security can be considered at the level of the individual through to families, nations, regions, and globally. The United Nations Food and Agriculture Organization (FAO) has an all-encompassing definition of "food security exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food to meet their daily needs and food preferences for an active and healthy life. Similarly, the United States Department of Agriculture (USDA) has the broad definition of "food security for a household means access by all members at all times to enough food for an active, healthy life. Food security includes at a minimum (a) the ready availability of nutritionally adequate and safe foods, and (b) an assured ability to acquire acceptable foods in socially acceptable ways (i.e. without resorting to emergency food supplies, scavenging, stealing, or other coping strategies)". At present, food security is manifest in various forms, ranging from a surfeit of foods giving rise to obesity-inducing conditions, through to transitory shortages, and then famine and widespread hunger. Poverty, hunger, and associated stresses have long-term intergenerational physiological and cognitive effects.

According to a series of reports from the FAO, over 800 million people are chronically hungry, around two billion suffer intermittent severe food shortages, and six million children die of hunger each year. Food security relates ultimately to supply and demand, and is affected by social stability, but demand has increased as the world population has exhibited more or less continuous growth since 1350 to reach the present level of over 6.97 billion. Population projections vary but the UN and the US Census Bureau project that the world's population will peak at 9.5 to 10 billion later this century and then may decline as poorer nations develop. A high-end UN estimate, however, points to a global population of 12 to 16 billion by 2100. Most projections, though, are based on the so-called demographic transition, which assumes that the developing world will replicate the European experience of declining birth and death rates noted in the last century.An overall slowdown in world population growth to 1.05% per year is expected between 2011 and 2020, compared with 1.20% in the previous decade. Even so, each year the equivalent of several large cities will be added to already populous countries. Different regions have markedly different rates of population growth. Countries in the Organisation for Economic Cooperation and Development (OECD) are already noting static or declining populations whereas growth remains high in Latin America, the Middle East, and sub-Saharan Africa.

Other than food products from fresh and marine waters where a hunter-gatherer existence predominates, most food production is derived from agricultural land that includes arable land, land under perennial crops, and permanent pasture. In 2008, the global agricultural land was estimated to be 48,836,976 km^2 whereas arable land was just 13,805,153 km^2 so that arable land *per capita* is now less than 0.20 hectare. Although the estimated total area of arable land fluctuates from year to year, there is a marked downward trend reflecting its loss when used for non-food-producing purposes, such as building, as well as long-term effects such as drought, endemic soil-borne pests and diseases, aggressive weed infestations, soil erosion, and soil salinity. Estimates of food loss and waste range between 30% and 50% of all food produced so substantial curtailment of waste, especially post-harvest, would ease the pressures on production. This is unlikely to take place in the near future so there is a profound need to increase the absolute level of production on a diminishing area of land unless more marginal land, natural habitats, and novel food-production methods are deployed in parallel with diminishing global biodiversity and the loss of environmental buffering afforded by permanent natural vegetation. Intensive production is inevitable, posing technological and social challenges, such as those concerning livestock welfare and the nature of food consumed.

The recent OECD/FAO Agricultural Outlook 2011-2020 report noted price turbulence in recent years leading to rising food-commodity prices. World population growth, demographic changes, rising energy costs, policy developments, and declining productivity growth were identified as key drivers. In real terms, prices are expected to average up to 20% higher for maize and 15% for rice compared with the previous decade. Poultry, beef, pig meat, and whole-milk powder will all increase significantly up to 2020. Profitability will be adversely affected by rising input costs. For most countries, the main pressures on inflation are increasing food prices and energy prices. It is clear that non-food crops such as those for biofuels and industrial biotechnology, essential to help address emissions controls, will compete with food crops for arable land.

The term sustainability has special resonance in agriculture and food security, and often encompasses policies and actions unrelated to sustainability *sensu stricto.* Nothing is sustainable indefinitely unless the Laws of Thermodynamics are rewritten. Relevant questions include: what is being sustained? For how long? For whose benefit? At what cost? Over what area? Using what criteria? Sustainable agriculture should imply that the farmer could generate a living going into the future. Farming abstracts resources from the soil and causes ecological disturbance; in order to carry on for a long time into the future, abstracted resources have to be replenished and any build-up of deleterious factors removed.

In agriculture, price affects profitability and prices are influenced globally by market demand and production efficiency, but also by the market-distorting combination of subsidies, tariffs, import and export restrictions, supermarket negotiating hegemony, political and legislative constraints on adopting new technologies, dietary preferences, transport and supply-chain costs, labour costs, publicity and marketing costs, effects of pests including weeds and diseases, taxation impositions, quality-assurance schemes, *etc.*Pricing rarely encompasses all externalities. Most environmental improvement schemes, especially those relating to cutting carbon-dioxide and other greenhouse-gas emissions, are heavily dependent on the vagaries of taxpayer subsidy: abundant in times of plenty but cut in recessionary times. Two relatively recent features in international agriculture likely to alter traded flows and commodity pricing are(a) the purchase of substantial rights to agricultural land by highly populated developing countries and sovereign funds in poorer developing countries, and (b) governmental involvement in the control of phosphate and potash reserves and mining.

The quality and quantity of plant produce capable of being grown in a growing cycle depends on the interacting influences of (a) the genetic constitution of the cultivar; (b) length of the growing season;(c) soil conditions including water and nutrient supply, allelopathic and allelomediatory effects, competing plants and weeds, and root temperature; (d) solar radiation, including radiant flux density, spectral composition, photoperiod; (e) atmospheric temperature (to include thermoperiodic effects), gaseous composition, and wind speed; (f) effects of pests and diseases; (g) chemical and physical characteristics of the harvested portions of crop plants that determine appearance, shape, size, aroma, texture, taste, processing ability, and the levels of key constituents; (h) the shape of the plant and the number of dormant and active growing points; (i) post-harvest handling and storage.

The OECD/FAO 2011-2020 report assumes optimistically that crop yields will continue to increase until 2020, but the rate of these improvements is likely to decline markedly if current policies persist. In fact, in concert with rapidly rising input costs, there is evidence of a sharp slowdown in productivity growth. There are relatively few major crop and livestock species all with relatively narrow genetic bases indicating vulnerability to rapidly adapting pests and diseases; high-yielding cultivars are less able to compete against their wild relatives. Productivity growth is strongly influenced by consumer dietary preferences and demands, with a noted long-term trend in dynamic developing economies of increasing consumption of meat, eggs, and dairy products as well as alcoholic beverages.

ENERGY

Contrasting with absolute reliance on human labour and livestock energy in many subsistence agricultural units, modern agriculture uses extensive amounts of fossil-fuel-derived energy throughout the production cycle of ground preparation (minimum-till, low-till and no-till methods collectively referred to as conservation tillage are best to sustain soil structure), planting (sowing), agronomic practices involving the application of agrochemicals and irrigation, horticultural lighting and ventilation, harvesting, storage and drying, and processing. Considerable amounts of fossil-fuel-derived energy are also used to manufacture nitrogenous fertilisers through the Haber-Bosch process especially as well as other agrochemicals, in addition to the manufacture and operation of farm machinery. In addition, energy is used in the construction, maintenance, and operation of often-complex agricultural, horticultural, and food-processing infrastructure. At this juncture, there are no thorough life-cycle analyses (LCAs) of agricultural products. LCAs need to take into account energy used in the elimination or utilisation of pre-gut food and agricultural wastes from domestic and industrial sources, as well as from contaminated or diseased materials. Such wastes are a source of greenhouse gases (GHG). Likewise, considerable amounts of energy are required for the elimination or utilisation of post-gut food wastes and non-food crop wastes. Ancillary problems arise from diet-derived pharmaceutical products, toxins, heavy metals, and antisocial aromas. Again, these wastes can be potent sources of GHG. Updating data provided by Pimentel and Pimentel [2008] if global food production, processing, and transport were to adopt the US model of consuming the equivalent of around 1500 litres of oil *per capita* then the known total oil supplies would be exhausted in 7 years. Reliable and cost-effective alternative and renewable sources of energy are needed, especially on farming units.

WATER

A combination of expanding populations, climate change, environmental degradation, unequal distribution of realisable natural resources and the capacity to produce food, poverty, and political and social incompatibilities means that a significant proportion of the global population has restricted access to fresh water, the products of marine and freshwater bodies, and transport routes that bodies of water can provide. In contrast, some are subject to the destructive forces of water such as floods, tsunamis, tropical cyclones, landslides, and avalanches. In turn, all these water-based problems create political and social instabilities, exacerbating poverty and ill-health, and diminishing human dignity.

Water availability is perhaps the immediate challenge for most farming systems throughout the world. Around 1000 litres of water are needed to produce one kg of maize grain (caryopses). Biofuel production is water-intensive; a litre of ethanol from maize or sugar beet involves the utilisation of 3500 to 5880 litres of water. In many respects, agricultural commodities can be regarded as a form of transporting water as well as nutrients. Modern lifestyles and many forms of agriculture and manufacturing industry have led to an inexorable rise in *per capita* consumption of fresh water. Water use increased six-fold over the last 100 years, a rate more than double the rate of population growth. Massive amounts of energy are needed to irrigate crops. Global climate change is expected to reduce total water availability for agriculture in most of the heavily populated areas of the world, as well as in some zones currently acting as the main sources of traded agricultural commodities. At present, only 17% of global agricultural land is irrigated, a figure expected to increase as rain-fed production becomes subject to irregular rainfall patterns. In many developing countries, agricultural irrigation accounts for 90% of freshwater usage and even in the USA around 30% of freshwater supplies are used for agricultural irrigation. Depletion of aquifers and fossil-water supplies, coupled to diversion of rivers for non-agricultural purposes and water pollution collectively pose huge problems for future food supplies. Pollution of water arises from excess leaching of mineral fertilizers (especially nitrates and phosphates), pesticides, herbicides, human sewage, livestock wastes, and untreated industrial wastes (contaminated with heavy metals, radionuclides, polychlorinated biphenyls, pharmaceuticals, and a prodigious variety of soluble and semi-soluble residues). The metabolic fates and consequences of most of the known 22,000 or so xenobiotics are unknown. Thermal pollution arises from the raised temperature of cooling waters used by power stations and heat-generating activities, both industrial and domestic. It has wide-ranging ecological effects, modifying the dissolved-oxygen levels and the composition and abundance of the flora and fauna in the area.

Water purification or treatment poses particular difficulties in urban areas and has to function with an increasing burden of bioactive xenobiotic contaminants as well as solid wastes, many of which are functionally non-biodegradable. Purification processes include slow and rapid filtration (the latter deploying coagulants), chlorination, UV treatments, desalination, and water softening by chemical precipitation or ion exchange to remove calcium and magnesium salts that would otherwise cause insoluble scale formation. Depending on how the output of sewage and wastewater plants is utilized (*e.g.* direct application to the land; subsurface disposal; non-potable ("grey water") for domestic, agricultural and industrial purposes; potable water), all regimes can be designed to deliver the desired end-product. Nonetheless, the residue (termed sludge) from treatment plants demands special attention. This involves thickening to aid further treatment, biological sludge digestion, dewatering, and then disposal. In these processes, the sludge is stabilized, deodorized, made biologically safe, and can be disposed of by using as a soil additive to improve fertility once any heavy metals have been removed, or used for non-food crops and forestry. Incineration or disposal in landfill sites or in seas and oceans are becoming unacceptable internationally.

Desalination of seawater has become one of the primary sources of water in arid zones. In order to make seawater fit for human consumption and for application to most crop species, its salt content must be reduced from approximately 3.5% to 0.5% or less. This can be achieved bydistillation and membrane processes. Traditional distillation has given way to more modern multistage flash-distillation plants, multiple-effect distillation plants, and the vapour-compression distillation system. Related processes include solar humidification in shallow basins or solar stills, and freezing (crystallization) to form crystals of pure ice. Distillation processes need energy of about 10 kWh m^{-3} of seawater processed. Membrane processes include electrodialysis and reverse osmosis, and are usually adopted with brackish waters rather than seawater. Generating the pressure needed to drive the molecular sieves that separate out the ions such as sodium and chloride responsible for the salinity consumes about 4 kWh m^{-3} of energy, although a system developed by Siemens in Singapore is claimed to consume only 1.8 kWh m^{-3} of energy. Reverse osmosis is becoming more common as a desalination process commensurate with the application of improved membranes and access to solar power in countries with high solar radiant flux levels. Even so, desalination produces brine as an effluent, the disposal of which can be a severe pollutant in inland areas unless efforts are made to recover valuable minerals.

The Earth's total water budget is around 1.4 billion m^3 with less than 1% available for human use. Some 97.5% is salt water (averaging 35g dissolved minerals and salts *per* litre) and the remainder is held in polar ice caps, glaciers, freshwater bodies, vegetation, groundwater, and atmospheric vapour. The hydrologic cycle is driven by solar radiation and gravity and involves mainly the processes of evaporation, transpiration, precipitation, interception, infiltration, subterranean percolation, overland flow, and run-off. This cycle has been modified by human activity such as deforestation and clearance of other vegetation types, eutrophication and contamination, construction and modification of streams and rivers, drainage systems, and unsustainable water-abstraction policies. Most authorities agree that approximately 70% of human water consumption occurs in Asia, with Asia now responsible for the annual withdrawal of over 2500 km^3 of freshwater and Europe over 600 km^3 ; consumption excluding irrigation amounts to about 1500 km^3 in Asia and 400 km^3 in Europe.

According to International Alert, 46 countries comprising a combined population of 2.7 billion people have been identified as at risk of violent conflict as a result of climate-change and water-related risks, with a further 56 countries comprising another 1.2 billion identified as at high risk of political instability. No matter the country, extreme food shortages rapidly lead to social breakdown.

Only by the adoption of a raft of water-saving, water-purification, and environmental-protection technologies will it be possible to guarantee the efficient functioning of agriculture and horticulture as well as manufacturing and service industries. Similarly, such measures are needed for the efficient functioning of domestic water supplies. Many agriculturalists determine crop production in terms of water needed to create a specified yield.

SOILS

Soil degradation and compaction affects most countries. Good agricultural practice, including maintaining organic matter levels, can be beyond the means both educational and cost of many subsistence farmers. Soil salinity is a particular problem that can arise from using poor irrigation practices and inappropriate groundwater supplies. Informal reports have noted marine-derived salt water driving into agricultural river basins, such as the Nile Delta, possibly as a result of thermal expansion of the seas and oceans. Another important consideration is that disturbed soils release GHG, especially peaty soils.

In terms of the climate-change debate, soils contain about three times the amount of carbon in surface vegetation and twice the amount in the atmosphere, namely 1500 Pg of organic carbon in soils compared with 560 Pg in vegetation. The annual fluxes of carbon dioxide from atmosphere to land (global net primary production) and land to atmosphere (through respiration and fire) are each in the order of 60 Pg of carbon *per* year. During the 1990s, fossil-fuel combustion and cement production emitted around 7 Pg of carbon to the atmosphere, and changes in land use emitted around 2 Pg of carbon a year. Atmospheric carbon has increased at around 3.2 Pg *per* year, the oceans absorbed around 2.5 Pg *per* year and are acidifying, and there is estimated to be a residual carbon sink of around 2.5 Pg a year. Historically, soils have lost between 40 to 90 Pg of carbon globally through cultivation and soil disturbance. Biological carbon sequestration is of profound importance in considering the impacts of all forms of energy generation. Bringing about a dramatic increase in soil-carbon content, such as by adding catalytic and absorptive carbon ("biochar"), thereby improving water retention and soil fertility is an urgent requirement for all forms of agriculture.

DIETARY PREFERENCES

Vegan and vegetarian diets have been regarded as the most energy-efficient and climate-friendly way to feed humans and diverse authorities have recommendeda reduction in meat consumption. The rapid rise in the quantities of meat fed to carnivorous pets in the western world has also raised questions about controls on pet numbers as a way to help curtail GHG. Massive amounts of cereals and oilseeds are used to feed livestock. Besides being major emitters of methane as well as other gases, livestock are inefficient converters of energy from plants. Crop plants at this stage of development are not highly efficient energy converters either. In addition to the relatively poor basic photosynthetic efficiency of higher plants, global agricultural production captures far less than 0.1% of the available solar energy in a typical growing season. About 25% of the solar energy captured by plants is used for metabolic processes in the plant rather than laid down as dry matter. Nevertheless, the plant matter produced by marginal pasture and rangeland is best suited to the feeding of cattle, sheep, and goats. Although it has inherent inefficiencies, this method of farming does not have the heavy carbon footprint of feedlot cattle production. It would be difficult to enforce vegetarian diets other than by shortages and/or extremely high costs; cultural demands and typical human nutritional requirements favour mixed diets.

ECONOMIC CONDITIONS

Many countries now suffer from current-account deficits, poor balance-of-payments positions, a growing public-sector wage and pension liability, a large consumer debt, off-balance-sheet liabilities, a weakened banking sector reluctant to lend to businesses, and a downward pressure on public spending. Declining corporation-tax income and a lack of private-sector investments compound this recessionary economic position and is leading to the downgrading of future growth forecasts. Economic climates of this type invariably lead to a sharp downturn in spending on aid to less-developed countries and to cuts in research and development funding in both the public and private sectors. Even in more favourable economic times, public-sector agricultural research and development in the advanced economies have been severely reduced and have become increasingly a private-sector activity, mainly in a few multinational companies. Western donor countries have trimmed aid budgets, reducing the effort on crops most relevant to poor countries. There has also been the tendency in many countries to regard applied research and development as inferior to basic or fundamental research, even when it has little direct societal benefit.

According to recent reports from the USDA, US maize stocks are at their lowest for 15 years and are 45% lower than last year. The forecast for 2011-2012 has been reduced to a record low, and next season more maize could be used to make ethanol than provide animal feed. Poultry and livestock farmers may be forced to lower their outputs.

The late Ian Carruthers, an economist at the former Wye College, University of London, reckoned in the 1980s that there will come a time in the next few decades when there will be a reversal in the terms of trade such that certain temperate countries will have to be the major source of foodstuffs to the expanding populations in water-stressed parts of the tropics and semi-tropics.

APPROACHES TO ADDRESS GLOBAL FOOD SECURITY

A combination of the following activities would assist in bringing about the concept of sustainable agriculture and global food security. There must be deep concerns about the reliable supply of foodstuffs to a global population of 10 billion even on the basis of current agricultural best practice; many countries are already facing fundamental food security problems regardless of projected deleterious climate-change projections. Fresh thinking is needed. Food security demands factoring in uncertainties about extreme events, such as ultimately transgressing the tipping point in the climate system, or more likely, major outbreaks of infectious diseases, pests, social unrest, trade disagreements, and wars.

1. Vertical and horizontal integration of farming-related businesses. This process is essential to enhance profitability, efficiency, and scale of operation, with adequate capitalisation to introduce new and more efficient technologies timeously as well as ensure effective supply-chain management. Integration means that in addition to automated farming and processing operations, adoption of best farming and environmental practices, and staff training, predictive modelling and expert systems will be widely adopted for pest and disease control and agronomic operations, weather forecasting, supply-chain management, and market intelligence.Knowledge-based farming brings with it greater understanding and appreciation of the spatiotemporal scale and complexity of agroecosystems. Subsidies are currently delaying rural adjustment to profound global changes in food-supply arrangements by sustaining essentially non-economically viable farming units, even though the subsidy system maintains small family-owned farms and cultural preferences for “old-fashioned” ways of farming.
2. Policy shifts on a multilateral basis are needed to remove market-distorting and innovation-suppressing influences such as subsidies, tariffs, import and export bans, and excessive bureaucracy. Switching some, if not all, of existing subsidy regimes to support research and development, and infrastructural improvement, would help bring about an agricultural renaissance. Governments should embark on establishing agricultural and food “roadmaps” to assist in helping the industry to grow the economically right species in the right place, and assist government in developing competition-enhancing

supportive processes and infrastructure. National and regional technology-foresight programmes involving coordination between all sectors of the food industry, the research and development community, government, and civil-society groups would be of benefit in constructing the roadmaps.

3. Crop breeding. Breeding is the single most important factor for arable and horticultural growers for gaining competitive advantage for themselves, for the nation, as well as the main means to adapt the industry to changing physical, social, and economic environments. Improved cultivars are often internationally valuable intellectual property. According to the multinational company Monsanto, breeding, especially with biotechnological tools, is the single most important factor for increasing food production, followed by improved agronomy and then reduced losses by pests and diseases. Essentially long term, crop breeding involves interdigitation with the public sector nationally and internationally for trained personnel, access to germplasm collections and gene banks, statutory testing arrangements, and access to repositories of important pests and diseases to challenge potential new cultivars. Breeding perennial woody species with long juvenile periods requires special effort using modern propagation and crossing technologies. Conventional plant breeding ("cross two of the best and hope for the best") is expensive and far too protracted to address the urgency of the need to ramp up food supplies and reduce GHG emissions without being supplemented by several of the newer selection and transgenic technologies. Crop-breeding targets include the following. (a) Enhancing photosynthetic efficiency to capture more solar energy and convert it into useful chemical forms. Even minor improvements to photosynthetic efficiency and plant design would profoundly raise global agricultural productivity and greatly assist in fixing carbon-dioxide emissions. (b) The ability of the main crop species to survive periods of drought and grow in the presence of brackish waters would increase the geographic range of cultivation. (c) Low-temperature tolerance would help extend growing seasons and assist with crop survival in unseasonably low temperatures. (d) An ability to control the timing of flowering and fruit and seed formation is possible with many horticultural species in environmental-control housing but has yet to be extended to extensive field-grown crops although various chemical triggers are promising research targets. (e) Broad-spectrum pest and disease resistance and tolerance characteristics need constantly to be introduced in the genomes of the main crop species, especially in monocultural systems, in order to adapt to the relentless adaptability of pathogens. Sometimes, new biotypes can be identified that need urgent attention of the breeders. (f) Improved water- and nutrient-use efficiency characteristics would lessen the need for inputs. (g) Improving the proportion of harvestable material in the plant would minimise waste. (h) Improved quality of the harvested material, such as chemical composition – for example biofortification, texture, dimensions, machine-harvestability, and durability will remain a key target. (i) Finally and not least, improved cost-effective yield increases are crucial to providing hope for feeding the global population in the years ahead.
4. Livestock breeding has somewhat similar aims. These include improved conversion of inputs into usable outputs, pest and disease resistance, yield, lifespan, reproductive capacity, tolerance to environmental perturbations, temperament, quality of the outputs (*e.g.* meat, milk, eggs, skin for leather),

and lowered emissions of GHG often by modifying diets and gut flora and fauna in both ruminants and monogastrics.

5. Agricultural and horticultural automation is a key feature of meeting the challenge to produce more food. Ground preparation, planting, harvesting, storage, processing, drainage, pollution control, compost and silage making, bioremediation, land stabilisation can all be automated and in its more advanced form warrants the term precision agriculture. An ability to separate the desired agricultural crop from unwanted weed propagules is an established capability of most harvesting machinery. Modern crop breeding and agronomy practices are carried out in concert with the development of new machinery. Improvements will lead to energy optimisation, water and agrochemical optimisation, improved quality control, less manual work, greater efficiency of operation, and uptake of new intellectual property. By way of illustration, horticultural crops once thought to be resistant to automatic picking (*e.g.* raspberries, blackcurrants, hops, apples) have been bred (with characteristics such as modified bush shape, long fruit-bearing laterals, lack of spines, uniform fruit ripening, fruit with better abscission layers and stronger epidermes) to withstand the rigours of machine harvesting.
6. Protected cropping will increase as a result of weather variability and the lack of reliable long-range weather forecasts. Already, the soft-fruit industry globally has been revolutionised by the introduction of polytunnels offering protection from adverse weather and better working conditions for pickers. Experiments with modifying the spectral transmission of different types of plastic have demonstrated major improvements in controlling insect attacks. Likewise, various types of horticultural fleece are increasingly being used to protect crops such as brassicas from insect attack. There will be more attention paid to windbreaks as well as irrigation, drainage, and cultivation systems to reduce run-off and erosion.
7. New crop and possibly new livestock species. The narrow genetic base of the main global crops means that new species need to be sourced from *circa* 250,000 to 400,000 naturally occurring angiosperms. Until now, there has been relatively little attention paid to an existing portfolio of crops classified as orphan (neglected by western countries but important to subsistence farmers), neglected generally, and under-utilised. Likewise, few attempts have been made to develop novel wild species but there is great potential in seeking new fibre, starch, lipid, and protein crops notwithstanding that regulatory hurdles abound in introducing new food crops. Compared with crops, more cultural barriers exist in introducing new forms of livestock.
8. New-generation agrochemicals. After more than a decade of disinvestment from developing and manufacturing agrochemicals, exacerbated by environmental concerns, a clear need exists for compounds with minimal unintended environmental effects. New active ingredients and their adjuvants, new methods of application, new monitoring systems, predictive modelling, and integration with agricultural engineering and transgenic technology represent exciting ground-breaking ways of increasing yield performance.
9. New agronomic practices are inevitable, particularly with the use of cultivar mixtures, extended rotations, charcoal, and reducing the amount of ploughing, but also cultivating crops in artificial systems and developing robust phytosanitary regimes. Cultivar mixtures will be needed to counteract the vulnerability of monocultural (single cultivar) systems to catastrophic attacks

by pests and diseases. This will need the agreement of food processors and customers. The adaptive capacity of agricultural systems (and agriculturalists) to minimise climatic and biotic impacts that will be more pronounced in the tropics than in the northern temperate zones, will mean widening rotations, improving crop mixes, and being alert to the impacts of gene-flow systems.Charcoal incorporation into the soil has many advantages in preventing nutrient leaching, binding toxins and other contaminants, locking up bound carbon dioxide, and increasing the level of organic matter with benefits for fertility. Greater adoption of no-till and low-till cultivation methods for shoot-harvested crops is restricted by current problems of weed control, soil-borne pest and disease treatments, and soil compaction. Therefore, automated monitoring of the weed-seed bank and soil pathogens should be accompanied by point-source killing of emerging weeds, breaking the dormancy of problem weeds and pest eggs in winter- or drought-killing conditions, and even byplough-mounted sheathed irradiation sources to sterilise badly infested soil. Present-day soil-sterilisation treatments use enormous amounts of energy, are dangerous, and can have long-term undesirable environmental effects; they are also not feasible in large-scale farming systems. Wholly artificial growth systems, such as hydroponics in glasshouses and small- to medium-scale cultivation *in vitro* of photosynthetic microorganisms to create novel food proteins, oils, carbohydrates, and other valuable compounds. Such systems can be greatly expanded in urban environments and can operate under extreme conditions using genes from extremophiles.

10. Novel foodstuffs. With urbanisation comes demand for convenience foods, usually highly processed and aggressively marketed. A wide range of bacterial, fungal, and protozoan species can supply essential nutrients and growth factors. Processing can create a vast array of interesting tastes, textures, and appearances ("Quorn" for example), and these organisms do not require normal agricultural land. Supplementing food supplies thus will reduce the trend of converting pristine habitats into arable land and releasing GHG.
11. Habitat reconstruction and land renovation. Protection of the native flora and fauna can be achieved with dispersal corridors and refugia, and various authors such as Lynas in *The God Species* and Phalan and co-researchers in Cambridge University have noted that nature-friendly agricultural systems are relatively lower-yielding systems that intensive systems and require larger areas to produce the same amount of food. This view is contested by some proponents of organic farming but is not contested by most agriculturalists. Likewise claims of superior soil maintenance in organic systems, many state-of-the-art agricultural units take care to build up soil organic matter. Intensive units separated by pristine habitats and dispersal corridors for flora and fauna represent the ideal solution. Regardless of selecting the type of agricultural practice, restoration of contaminated, eroded, and neglected land is a pressing requirement in most countries. Novel bioremediation technology involving accumulators and metabolisers of toxic compounds, waste recycling, access to germplasm collections of native flora, and advanced analytical chemistry are beginning to be used in conjunction with conventional land reclamation schemes.

12. Biofuels and biodiesel. In theory, “carbon-neutral” biofuels capitalise on a closed system of photosynthetic carbon capture (to form reduced compounds) followed by carbon release when the fuels are combusted (oxidised). Most biofuels are formed by the fermentation of starchy or cellulosic feedstocks, such as ethanol or butanol, or by direct conversion of extracted plant oils to form biodiesel. Patent-protected genetic-modification technologies to enhance carbohydrate and lipid levels in crop plants and create modified microorganisms to generate high-calorific-value end products. Undesirable side effects of governmental drives to foster biofuel production from conventional crops include the diversion of arable land for much-needed food crops into fuel production. Subsidies make this conversion of land use possible even where the energy balance (ratio of the energy yielded by a given quantity of biofuel to the energy needed to create it) is unfavourable.
13. Periurban and urban agriculture. Urbanisation has prompted numerous initiatives to cultivate horticultural crops and livestock in settlements, towns and cities wherever planning regulations permit or are ignored. Open spaces, rooftops, balconies and window ledges can support local food production and even contribute to the “greening” of the area, and in many instances can improve the visual amenity and enhance biodiversity. Vegetation is an effective “scrubber” of contaminated air. Many of those involved believe that it is just as well to cultivate edible plants rather than ornamentals, and feel reconnected with their rural heritage. Neighbours can be inconvenienced especially with livestock and there is always the problem of contamination from unsuitable growing media and air pollution. In the future, periurban and urban agriculture will undoubtedly become an important source of food. People living in huge urban conurbations are heavily dependent on efficient supply chains from the primary-producer network.
14. Industrial biotechnology. Advances in industrial biotechnology are offering new ways to save, purify, and recycle water. Biorenewables are substituting for materials that are sourced either through major environmental disturbance (such as metals) or through fossil fuels (such as most plastics). New types of second- and third-generation fuels are beginning to replace fossil fuels. Related biotechnology such as recombinant antibodies and nucleic-acid-based techniques are producing new forms of diagnostics for disease assessments of food and water. Advances in agricultural biotechnology offer a wide range of crops with desirable characteristics and new food products employing nanotechnology. Integral to the advancement of biotechnology are new types of analytical and physical chemistry, information and communications technology, bioinformatics, and organismal biology.
15. Farming the seas and oceans. With the exception of coastal waters, the oceans are not “farmed” sustainably to harvest fish, algae, and other life forms. There are severe international disagreements over the “ownership” of mineral, oil, and gas reserves under continental shelves and isolated islands. Most countries recognise national ownership of fish and crustacean stocks in coastal waters where an increasing amount of aquaculture is taking place. The days of having a fishing industry largely based on a hunter-gatherer mode of existence is coming to an end as the demand for fish and related life forms and the fishing technology greatly exceeds the reproductive capacity of the desired species. There are massive losses caused to unintended netted species, too. Fish and shellfish farming in the seas and oceans must become the norm if as expected

the global population continues to rise in the coming decades. Likewise, the cultivation of marine and freshwater algae for food and industrial feedstocks, and as a source of energy and fertiliser, will come to the fore. Containment facilities will need to be developed, and strategies put in place to breed and propagate, and replace abstracted nutrients.

16. Long-term carbon storage. Deep-burial storage of liquefied carbon dioxide from carbon-capture units attached to fossil-fuel-burning energy generation stations is fraught with danger in respect of the potential for catastrophic release from subterranean ground movement and insecure sealing, perhaps further acidifying the oceans and rapidly altering atmospheric composition. Moreover, the carbon-capturing processes are energy-intensive and have yet to prove value-for-money. Long-term storage of fixed carbon can arise on land by using timber (xylem and cork) and other plant products such as fibres for industrial and construction purposes, delaying therefore carbon recycling possibly for centuries. Careless deforestation without timber replacement dramatically releases GHG besides having other severe environmental knock-on effects. In the seas and oceans, “marine snow” comprising live and dead planktonic cells, secretions, dead animals, and faecal materials sink into deep waters and represent a form of locking away carbon. A small proportion becomes part of sedimentary rock; the remainder can be recycled at various times by upwelling and eddy diffusion. At present, phytoplankton in oceans and seas that cover around 75% of the Earth’s surface incorporate about 45-50 billion tonnes of inorganic carbon into their cells and about 8 billion tonnes of this carbon are transferred to the deep oceans as marine snow. Plants in terrestrial habitats fix about 60 billion tonnes of carbon dioxide a year. Encouragement of oceanic photosynthesis by supplying growth-limiting nutrients, especially iron, is feasible. Other nutrients are also needed such as combined nitrogen and potassium as phosphates. Inadvertent eutrophication already demonstrates the effects of nutrients on photosynthetic organisms in both fresh and marine coastal waters. Clearly, it is far better to constrain GHG emissions, but photosynthetic capture of carbon dioxide remains the single most effective way to amend thechemical composition of the atmosphere without resorting to geoengineering.
17. Carbon trading. Fixing a price on carbon emissions and trading offsets may not be the best way to address the climate-change challenge or assist is securing global food security. Carbon-dioxide emissions are not a commodity *per se*; the scheme is essentially trading a penalty, a negativity, and is dependent on a combination of auditors and regulators of variable quality who may be prey to preferential political and pressure-group coercion, as well as fraud and speculation. Carbon trading in its present form requires perhaps an unachievable level of international transparency and integrity, and it is currently attracting speculators packaging carbon credits into complex financial products. Independently vetted proper carbon accounting (carbon “footprints”), energy-expenditure analyses, emission-control regulations, and thorough life-cycle analyses need to be implemented as a matter of urgency. Carbon trading is not being built upon strong foundations at present despite enthusiastic involvement of various quasi-public bodies and market traders. It is not too late to reverse direction, however, and trade positively in the form of various kinds of fixed carbon, namely agricultural and maritime commodities, tangible expressions of fixed carbon, diamonds of global food security.

CONCLUSIONS

Global food security is a never-ending quest as the global population increases with its relentless demands on natural resources. It is not simply a matter of providing sufficient energy to seven billion or more increasingly affluent humans without burning up the planet (volcanism-induced cooling notwithstanding), it is a matter of feeding them meantime. In terms of global biodiversity, the effectiveness of existing measures to establish protected areas will not be able to overcome losses in both terrestrial and marine environments according to Mora and Sale (2011); they recommended new protection strategies and stabilising the human population and its ecological demands. Although adequately supported science, engineering, and technology can provide answers, only a suitable and peaceful political climate can provide an appropriate framework for action. Time is of the essence; delay in taking action will cause misery for many.

REFERENCESCONSULTED

Blaschek, H.P., Ezeji, T.C.,Scheffran, J. Eds. Biofuels from Agricultural Wastes abd Byproducts. Wiley-Blackwell, Iowa, 2010. ISBN 978-0-8138-0252-7

Foresight. The Future of Food and Farming. Final Project Report. 2011. The Government Office for Science, London

Hillman, J.R. Report of the Director. Annual Report of the Scottish Crop Research Institute for 2003/2004. 2004. Scottish Crop Research Institute, Dundee, UK, pp. 11-100. www.scri.ac.uk/

Hillman, J.R., Baydoun, E. An Overview on Alternative Energy and Renewable Sources of Energy. 2010. Proceedings of the International Conference on "Alternative and Renewable Sources of Energy" pp. 38-62. Organised by the Arab Academy of Sciences and ISESCO. Beirut, Lebanon. (25-26 November 2010)

Hillman, J.R., Watson, D.H., Brooks, D.H., Casey, J., Clift, R., Crabtree, M., Cubitt, I., Cutler, A., Eggington, A., Gill, B., Heap, R.B., Lawton, J.H., Marsh, J.S., Mather, J., McConnell, I., Meyer, M., Owens, S.E., Parkes, D., Pentreath, R.J.,Roberts, N.J., Shannon, D.W.F., Tinsley, M., Turner, R.K. Technology Foresight: Progress Through Partnership, Volume 11, Agriculture, Natural Resources and Environment. HMSO. 1995

Lynas, M. The God Species. How the Planet Can Survive the Age of Humans. HarperCollins, London. 2011. ISBN 978-0-00-731342-6

MacKay, D.J.C. Sustainable Energy – Without the Hot Air. UIT Cambridge, 2008. ISBN 978-0-9544529-3-3

MacKerron, D.K.L., Hillman, J.R., Duncan, J.M. Sustainability in agriculture. Annual Report of the Scottish Crop Research Institute for 2001/2002. 2002. Scottish Crop Research Institute, Dundee, UK, pp. 69-82. www.scri.ac.uk/

Mora, C., Sale, P.F. Ongoing global biodiversity loss and the need to move beyond protected areas: a review of the technical and practical shortcomings of protected areas on land and sea. Mar. Ecol. Prog. Ser. 2011;**434**; 251-266

Phalan, B., Onial, M., Balmford, A., Green, R.E. Reconciling food production and biodiversity; landsharing and land sparing compared. Science 2011;**333**; 1289-1291

Pimental, D., Pimental, M.H. Food, Energy, and Society. Third Edition. CRC Press, Boca Raton, FL. 2008. ISBN 978-1-4200-4667-0

von Weizsacker, E., Hargroves, K., Smith, M.H., Desha, C., Stasinopoulos, P. Factor Five. Transforming the Global Economy through 80% Improvements in Resource Productivity. The Natural Edge Project. Earthscan, London & Sterling, VA. 2009. ISBN 978-1-84407-591-1

Yadav, S.S., Redden, R.J., Hatfield, J.L., Lotze-Campen, H., Hall, A.E. Eds. Crop Adaptation to Climate Change. First Edition. John Wiley & Sons Ltd., Chichester, UK. 2011. ISBN 978-0-8138-2016-3

Yergin, D. The Quest: Energy, Security and the Remaking of the Modern world. Penguin Press. 2011. ISBN 9781846145421

WEBSITES OF ORGANISATIONS CONSULTED

CGIAR (originally the Consultative Group on International Agricultural Research) and the CGIAR Centers: www.cgiar.org/
Crops for the Future (merger of the Global Facilitation Unit for Underutilized Species (GFU) and the International Centre for Underutilised Crops (ICUC)): www.cropsforthefuture.org
International Alert: www.international-alert.org/
International Food Policy Research Institute: www.ifpri.org/
International Fund for Agricultural Development: www.ifad.org/
Intergovernmental Panel on Climate Change: www.ipcc.ch/
International Energy Agency: www.iea.org/
United Nations Development Programme: www.undp.org/
United Nations Food and Agriculture Organization: www.fao.org/
United NationsEducational, Scientific and Cultural Organization: www.unesco.org/
United Nations World Food Programme: www.wfp.org/
United States Department of Agriculture: www.usda.gov/
United States Census Bureau: www.census.gov/
World Bank Group: www.worldbank.org/