The Vertical Farm:

Reducing the impact of agriculture on ecosystem functions and services

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Abstract

The advent of agriculture has ushered in an unprecedented increase in the human population and their domesticated animals. Farming catalyzed our transformation from primitive hunter-gatherers to sophisticated urban dwellers in just 10,000 years. Today, over 800 million hectares is committed to soil-based agriculture, or about 38% of the total landmass of the earth. It has re-arranged the landscape in favor of cultivated fields at the expense of natural ecosystems, reducing most natural areas to fragmented, semi-functional units, while completely eliminating many others. A reliable food supply was the result. This singular invention has facilitated our growth as a species to the point now of world domination over the natural world from which we evolved. Despite the obvious advantage of not having to hunt or scavenge for our next meal, farming has led to new health hazards by creating ecotones between the natural world and our cultivated fields. As the result, transmission rates of numerous infectious disease agents have dramatically increased- influenza, rabies, yellow fever, dengue fever, malaria, trypanosomiasis, hookworm, schistosomiasis – and today these agents emerge and re-emerge with devastating regularity at the tropical and sub-tropical agricultural interface. Modern agriculture employs a multitude of chemical products, and exposure to toxic levels of some classes of agrochemicals (pesticides, fungicides) have created other significant health risks that are only now being sorted out by epidemiologists and toxicologists. As if that were no enough to be concerned about, it is predicted that over the next 50 years, the human population is expected to rise to at least 8.6 billion, requiring an additional 10^9 hectares to feed them using current technologies, or roughly the size of Brazil. That quantity of additional arable land is simply not available. Without an alternative strategy for dealing with just this one problem, social chaos will surely replace orderly behavior in most over-crowded countries. Novel ways for obtaining an abundant and varied food supply without encroachment into the few remaining functional ecosystems must be seriously entertained. One solution involves the construction of urban food production centers - vertical farms – in which our food would be continuously grown inside of tall buildings within the built environment. If we could engineer this approach to food production, then no crops would ever fail due to severe weather events (floods, droughts, hurricanes, etc.). Produce would be available to city dwellers without the need to transport it thousands of miles from rural farms to city markets. Spoilage would be greatly reduced, since crops would be sold and consumed within moments after harvesting. If vertical farming in urban centers becomes the norm, then one anticipated long-term benefit would be the gradual repair of many of the world's damaged ecosystems through the systematic abandonment of farmland. In temperate and tropical zones, the re-growth of hardwood forests could play a significant role in carbon sequestration and may help reverse current trends in global climate change. Other benefits of vertical farming include the creation of a sustainable urban environment that encourages good health for all who choose to live there; new employment opportunities, fewer abandoned lots and buildings, cleaner air, safe use of municipal liquid waste, and an abundant supply of safe drinking water.

Introduction

As of January 2006, approximately 800 million hectares of arable land were in use, allowing for the harvesting of an ample food supply for the majority of a human population now in excess of 6.4 billion. These estimates include grazing lands (formerly grasslands) for cattle, representing nearly 85% of all land that could support a minimum level of agriculture. Farming also produces a wide variety of grains that feed millions of head of cattle and other domesticated farm animals (1). In 2003, nearly 33 million head of cattle were produced in the United States, alone (2). In order to support this large a scale of agricultural activity, millions of hectares of hardwood and coniferous forest (temperate and tropical), grasslands, and wetlands were sacrificed, or at the very least severely reduced to fragmented remnants of their former ranges. In either case, significant loss of biodiversity and disruption of ecosystem functions on a global scale has been the result (3-5).

While no one questions the value of farming in getting us to this point in our evolutionary history, even our earliest efforts caused irreversible damage to the natural landscape, and is so wide-spread now that it threatens to alter the rest of the course of our life on this planet. The silt-laden soils of the floodplains of the Tigris and Euphrates River valleys serve as a good example in this regard (6). This region was the cradle of western civilization attributable solely to the early invention of food growing technologies (mostly wheat cultivation). The land was soon degraded below a minimum level of food production due to erosion caused by intensive, primitive farming practices that rapidly depleted the earth of its scant supply of nutrients, while mis-managed irrigation projects were often interrupted by wars and out-of-season flooding events. Traditional farming practices (i.e., non-high tech) continue to this day to produce massive loss of topsoil (3,5,6), while excluding the possibility for long-term carbon sequestration in the form of trees and other permanent woody plants (7).

Agrochemicals, especially fertilizers, are used in almost every commercial farming scheme (8), due to the demand for cash crops that require more nutrients from the substrate that it can provide. Fertilizer use is expensive and encourages the growth of weeds, making herbicide use almost a requirement (9). In commercial ventures, farming involves the production of single crop species, most of which are vulnerable to attack from a wide variety of microbes and arthropods (10,11). The agrochemical industries have, over just a short period of time (50+yrs), responded to these biological pressures, producing an astounding array of chemical deterrents that have, up to very recently, been able to control these unwanted guests attempting to sit at our table. The regular application of pesticides and herbicides has facilitated an ever-increasing agricultural bounty, but many arthropod and plant species have developed at least some level of resistance to both classes of compounds. As the result, higher and higher doses of these products are needed to do the same job as the year before. This is why the single most damaging source of pollution is agricultural runoff (12). In the majority of intensive farming settings following even mild rain events, a toxic mix of agrochemicals leaves the fields and contaminates surrounding ecotones with predictable regularity. The ecological consequences of runoff have been nothing short of devastating (13; see also USGS web site: http://www.usgs.gov). Human health risks are also undoubtedly associated with high exposures to some agrochemicals, and some illnesses associated with them have been identified (14). However, many chemicals manifest their toxic effects in the human body in ways far more subtle than, say for instance DDT and the thinning of birds of prey egg-shells, making them difficult to implicate in the disease process (15).

Farming itself is an activity fraught with health risks (16-23). The mechanisms of transmission for numerous agents of disease (e.g., the schistosomes, malaria, some forms of leishmaniasis, geohelminths) are linked to a wide variety of traditional agricultural practices (e.g., using human feces as fertilizer, irrigation, plowing, sowing, harvesting; 24-29). These illnesses take a huge toll on human health, disabling large populations, thus removing them from the flow of commerce, and this is especially the case in the poorest countries. In fact, they are often the root cause of their impoverished situation. Trauma injuries are considered a normal consequence of farming by most who engage in this activity (25,30,31), and are particularly common among "slash and burn" subsistence farmers. It is reasonable to expect that as the human population continues to grow, these problems will worsen at ever increasing rates.

To address these problems and those perceived to soon emerge onto the horizon, an alternate way of food production was proposed; namely growing large amounts of produce within the confines of high-rise buildings. This idea appeared to offer a practical, new approach to preventing further encroachment into the already highly altered natural landscape (32: www.verticalfarm.com). The Vertical Farm Project was established in 2001, and is an on-going activity at the Mailman School of Public Health at Columbia University in New York City. It is in its virtual stages of development, having survived 4 years of critical thinking in the classroom and worldwide exposure on the internet to become an accepted notion worthy of consideration at some practical level. We have identified an extensive list of reasons why vertical farming may represent a viable solution to global processes as diverse as hunger, population growth, and restoration of ecological functions and services (e.g., returning land to natural process, carbon sequestration, etc.). If vertical farming (VF) were to become widely adopted, then the following advantages would most likely be realized:

1. Year-round crop production; 1 indoor acre is equivalent to 4-6 outdoor acres or more, depending upon the crop (e.g., strawberries: 1 indoor acre = 30 outdoor acres).
2. VF holds the promise of no crop failures due to droughts, floods, pests, etc..
3. All VF food will be grown organically employing chemically defined diets specific to each plant and animal species: no herbicides, pesticides, or fertilizers.
4. VF eliminates agricultural runoff.
5. VF would allow farmland to be returned to the natural landscape, thus restoring ecosystem functions (e.g., increases biodiversity) and services (e.g., air purification).
6. VF would greatly reduce the incidence of many infectious diseases that are acquired at the agricultural interface by avoiding use of human feces as fertilizer for edible crops.
7. VF converts black and gray water into potable water by engineering the collection of the water realized through evapotranspiration.
8. VF adds energy back to the grid via methane generation from composting non-edible parts of plants and animals.
9. VF dramatically reduces fossil fuel use (no tractors, plows, shipping.).
10. VF eliminates much of the need for storage and preservation, thus reducing dramatically the population of vermin (rats, mice, etc.) that feed on reserves of food.
11. VF converts abandoned urban properties into food production centers.
12. VF creates sustainable environments for urban centers.
13. VF creates new employment opportunities.
14. We cannot go to the moon, Mars, or beyond without first learning to intensively farm indoors on earth.
15. VF may prove to be useful for integrating into refugee camps.
16. VF offers the real possibility of measurable economic improvement for tropical and subtropical LDCs. VF may become a catalyst in reducing or even reversing the current trend in population growth of LDCs, as they adopt urban agriculture as a strategy for sustainable food production.
17. VF could reduce the incidence of armed conflict over natural resources, such as water and land for agricultural use.
18. VF could provide year round production of medically valuable plants (e.g., the anti-malarial plant-derived artemesinin).
19. VF could be used for the large-scale production of sugar (sucrose) to be used in the revolutionary new method for the production of non-polluting gasoline.

Defining the vertical farm

Indoor farming (e.g., hydroponics and aeroponics) has existed for some time. Strawberries, tomatoes, peppers, cucumbers, herbs, and spices grown in this fashion have made their way to the world's markets in quantity over the last 5-10 years. Most of these operations are small when compared to factory farms, but unlike their outdoor counterparts, they produce crops year-round. Japan, Scandinavia, New Zealand, the United States, and Canada have thriving greenhouse industries. Freshwater fishes (e.g., tilapia, trout, stripped bass, carp), and a wide variety of crustaceans and mollusks (e.g., shrimp, crayfish, mussels) have also been commercialized in this way. Fowl and pigs are well within the capabilities of indoor farming, and if we were to proceed to do so, offers some interesting advantages in addition to providing the world with a convenient food supply. For example, if chickens and ducks were to be raised entirely indoors, then the current epidemic of avian influenza might well have been aborted, or at the very least, significantly reduced in scope. None have been configured as multi-story entities. In contrast, cattle, horses, sheep, goats, and other large farm animals seem to fall well outside the paradigm of urban agriculture.

What is proposed here differs radically from what currently exists; namely to scale up the scope of operations, in which a wide variety of produce is harvested in quantity enough to sustain even the largest of cities without significantly relying on resources beyond the urban footprint. Our group has determined that a single vertical farm with an architectural footprint of one square New York City block and rising just 30 stories (approximately 3 million square feet) could provide enough calories (2,000 cal/day/person) to comfortably accommodate the needs of 50,000 people, and mainly by employing technologies currently available. Constructing the ideal vertical farm with a far greater yield per square foot will require additional research in many areas – hydrobiology, material sciences, structural and mechanical engineering, industrial microbiology, plant and animal genetics, architecture and design, public health, waste management, physics, and urban planning, to name but a few.

Yet, despite my obvious enthusiasm for the idea, I offer this note of caution. High-rise food-producing buildings will only succeed if they function by mimicking ecological process; namely by safely and efficiently re-cycling everything organic, and re-cycling "used" water (e.g., human and animal waste), turning it back into drinking water. Most important, there must be strong, government-supported economic incentives to the private sector, as well as to universities and local government to fully develop the concept. Ideally, vertical farms must be cheap to construct, durable and safe to operate, and independent of economic subsides and outside support (i.e., show a profit at the end of the day). If these conditions can be realized through an ongoing, comprehensive research program, urban agriculture could provide an abundant and varied food supply for the 60% of the people that will be living within cities by the year 2030 (33).

Some "proofs of concept"

1. Year round crop production

Traditional farming takes place over an annual growth cycle that is wholly dependent upon what happens outside, so farming remains one of the most precarious ways to make a living (why else have crop insurance!). Significant deviation (e.g., drought or flood) for more than several weeks away from conditions necessary for insuring a good yield has predictable, negative effects on the lives of millions of people dependent upon those items for their yearly food supply (34,35,36). Every year, somewhere in the world, crops suffer from too little water and wither on the spot, or are lost to severe flooding, hailstorms, tornados, earthquakes, hurricanes, cyclones, fires, and other destructive events of nature. Many of these phenomena are at best difficult to predict, and at worst are impossible to react to in time to prevent the losses associated with them. Climate change regimens (37) will surely complicate an already complex picture with respect to predicting crop yields (38-40).

In addition to losses due to bad weather events, an unavoidable portion of what is grown spoils in the fields prior to harvest time. Another large portion of harvest, regardless of the kind of plant or grain, is laid waste by a variety of opportunistic life forms (i.e., fungi, bacteria, insects, rodents) after storage. In Africa, locusts remain an ever-present threat (41), devastating vast areas of farmland in just days. Finally, armed conflict halts all normal human activity in any given war zone. Faming usually suffers greatly during those stressful times, with crops being burned or otherwise made unavailable by those wishing to severely limit the opposition's access to a reliable food supply.

Vertical farming obviates all external natural processes as confounding elements in the production of food. Growing food within urban centers will lower or even eliminate the consumption of fossil fuels needed to deliver them to the consumer, and will eliminate forever the need for burning fossil fuels during the act of farming. So where does the energy come from that is needed to run the vertical farm? Ideally, they will take full advantage of technologies centered around methane digestion of the inedible portions of what is grown (i.e., biogas production). Solar, wind, and tidal power could also contribute to reducing their dependence on fossil fuels (42,43). Iceland and other geologically active regions (e.g., Italy, New Zealand) will have the distinct advantage of harnessing geothermal energy, which they have at their disposal in abundance.

2. No-cost restoration of ecosystems: the principle of benign neglect

Converting most food production to vertical farming holds the promise of restoring ecosystem services and functions (44). There is good reason to believe that an almost full recovery of many of the world's endangered terrestrial ecosystems will occur simply by abandoning farmland and allowing the countryside to "cure" itself (45). This belief stems, in part, from numerous anecdotal observations as to the current biological state of some regions that were once severely damaged either by now-extinct civilizations or by over-farming, and, in part, from data derived from the National Science Foundation-sponsored long-term ecological research program (LTER), begun in 1980, on a wide variety of fragmented ecosystems purposely set aside for study subsequent to an extended period of encroachment (46). One of the most intensively studied of these fragmented ecozones is Hubbard Brook in northern New Hampshire (47-51). The area is a mixed boreal forest watershed that has been extensively harvested at least three times in modern times (1700s-1967). The Hubbard Brook LTER lists its research objectives as: vegetation structure and production; dynamics of detritus in terrestrial and aquatic ecosystems; atmosphere-terrestrial-aquatic ecosystem linkages; heterotroph population dynamics; effects of human activities on ecosystems. A portion of the watershed was clear-cut and the trees left in place, in contrast to farming regimes in which trees are removed to make way for crop production. Re-growth of some plants (shade intolerants) occurred within 3 years. By 20 years, the trees (shade tolerant plants) grew back to the same density as before the experiment was begun. These data give credence to the hypothesis that if vertical farming could replace most horizontal farming, then ecosystem services that reinforce a healthy life style (e.g., clean water, clean air, carbon sequestration) would be restored.

3. Urban sustainability

Natural systems function in a sustainable fashion by recycling all essential elements for the next generation of life (52). One of the toughest challenges facing urban planners is trying to incorporate the concept of sustainability into waste (both solid and liquid) management. Even in the best of situations, most solid waste collections are compacted and relegated to landfills. In a few rare instances they are incinerated to generate energy (53,54). Liquid wastes are processed, then treated with a bactericidal agent (e.g., chlorine) and released into the nearest body of water (55). More often than not in less developed countries, it is discarded without treatment, greatly increasing the health risks associated with infectious disease transmission due to fecal contamination (56). From a technological perspective, all solid waste can now be efficiently re-cycled (returnable cans, bottles, cardboard packages, etc.) and/or used in energy generating schemes with standard methods that are currently in use (57). Incorporating modern waste management strategies into the vertical farm model should work the first time out without the need for new technologies to come to the rescue. It must be emphasized that urban sustainability will only be realized through the valuing of waste as a commodity, deemed so indispensable that to discard something –anything - would be analogous to siphoning off a gallons' worth of gasoline from the family car and setting it on fire.

Since agricultural runoff despoils vast amounts of surface and groundwater 58-62), any water that emerges from the vertical farm should be drinkable, re-cycling it back into the community that brought it to the farm to begin with. Harvesting water generated from evapo-transpiration appears to have some virtue in this regard, since the entire farm will be enclosed. A cold brine piping system could be engineered to aid in the condensation and harvesting of moisture released by plants. The only perceived missing link is the ability to easily handle untreated human and animal wastes in a safe and efficient fashion. Several varieties of new technology may be required. Perhaps lesions learned from the nuclear power industry in handling plutonium and enriched uranium may prove helpful in designing new machinery for this purpose.

4. Social benefits of vertical farming

The social benefits of urban agriculture offer a rewarding set of achievable goals. The first is the establishment of sustainability as an ethic for human behavior (63,64). This ecological concept is currently a property of the natural world, only. Ecological observations and studies, beginning with those of Teal (65), showed how life behaves with regards to the sharing of limited energy resources. Tight knit assemblages of plants and animals evolved into trophic relationships that allowed for the seamless flow of energy transfer from one level to the next, regardless of the type of ecosystem in question (66). In fact, this is the defining characteristic of all ecosystems. In contrast, humans, although participants in all terrestrial ecosystems, have failed to incorporate this same behavior into their own lives. If vertical farming succeeds, it will establish the validity of sustainability, irrespective of location or life form. Vertical farms could become important learning centers for future generations of city-dwellers, demonstrating our intimate connectedness to the rest of the world by mimicking the nutrient cycles that once again can take place in the natural world that has re-emerged around them as the result of returning land back to the natural landscape. By transforming cities into entities that nurture the best aspects of the human experience is the goal of every city planner, and with vertical farming serving as a centerpiece, this concept has a real chance to succeed. Given the strength of resolve and insight at the political and social level, vertical farming has the potential to accomplish what has been viewed in the past as nearly impossible and highly impractical. Finally, to insure their continued success, we need to construct them in so desirable a way that every neighborhood will want one for their very own.

References

1. Food and Agriculture Organization, World Health Organization. 2004 statistics on crop production (available online).
2. United States Department of Agriculture. 2003 report on cattle production (available online).
3. FAO: The State of Food Insecurity in the World 2005
4. The Diversity of Life. Edward O. Wilson. W.W. Norton & Company, Pubs. 1992.
5. Pilot Analysis of Global Ecosystems. Agroecosystems. Wood, S, Sebastian K, and Scherr, S.J. 2001. International Food Policy Institute and World Resources Institute.; Internat. Food Pol. Res. Inst. and World Res. Inst., Washington, D.C. Pubs.; (also online at: http://www.wri/org/wr2000)
6. Hillel D. Out of the earth. Civilization and the life of the soil. University of California Press. Berekely, CA. 1991. P. 321.
7. Williams M. Deforesting the Earth. The University of Chicago Press. Chicago and London. 2003. P. 689.
8. IFA Agriculture Committee. Summary Report. Global Agricultural Situation and Fertilizer Consumption in 2000 and 2001. June 2001. (available online)
9. http://www.agron.iastate.edu/~Weeds/ag317/manage/herbicide/herbintro.html
10. http://www.ars.usda.gov/research/programs/programs.htm?np_code=303
11. http://www.usda.gov/wps/portal/!ut/p/_s.7_0_A/7_0_1OB?navid=SEARCH&q=pest+control
12. 2002 National Assessment Database, Environmental protection Agency.
13. Silent Spring. Rachel Carson. Houghton Mifflin Company, NY, NY. Pub. 1962.
14. Zupan J. 2003. Perinatal mortality and morbidity in developing countries. A global view. Med Trop 63:366-8.
15. 15. Ott MG. Exposure assessment as a component of observational health studies and environmental risk assessment. Scand J Work Environ Health. 2005;31 Suppl 1:110-4
16. Wang MJ, Moran GJ. 2004. Update on emerging infections: News from the centers for disease control and prevention. Ann Emerg Med. 43:660-2.
17. Molyneux DH. 2003. Common themes in changing vector-borne disease scenarios. Trans R Soc Trop Med Hyg. 97:129-32.
18. Stromquist AM, Burmeister LF, et al. 2003. Characterization of agricultural tasks performed by youth in the Keokuk County Rural Health Study. Appl Occup Environ Hyg. 18:418-29.
19. Park H, Reynolds SJ, et al. 2003. Risk factors for agricultural injury: a case-control analysis of Iowa farmers in the Agricultural Health Study. J Agric Saf Health. 9: 5-18.
20. Radon K, Monoso E, et al. 2002. Prevalence and risk factors for airway diseases in farmers--summary of results of the European Farmers' Project. Ann Agric Environ Med. 9:207-13.
21. Walker-Bone K, Palmer KT. 2002. Musculoskeletal disorders in farmers and farm workers. Occup Med. 52:441-50.
22. Sprince NL, Park H, et al. 2002. Risk factors for machinery-related injury among Iowa farmers: a case-control study nested in the Agricultural Health Study. Int J Occup Environ Health. 8:332-8.
23. Coble J, Hoppin JA, et al. 2002. Prevalence of exposure to solvents, metals, grain dust, and other hazards among farmers in the Agricultural Health Study. J Expo Anal Environ Epidemiol. 12:418-26.
24. Parasitic Diseases, 5th ed. Despommier, D, Gwadz, R.G., Hotez, P., and Knirsch, C. 2005. Apple Trees Producitons, LLC, Pub.
25. Merchant JA, Stromquist AM, et al. 2002. Chronic disease and injury in an agricultural county: The Keokuk County Rural Health Cohort Study. J Rural Health. 18:521-35
26. Zaki A, Bassili A, et al. 2003. Morbidity of schistosomiasis mansoni in rural Alexandria, Egypt. J Egypt Soc Parasitol. 33:695-710
27. Needham C, Kim HT, et al. 1998. Epidemiology of soil-transmitted nematode infections in Ha Nam Province, Vietnam. Trop Med Int Health. 3:904-12.
28. Fashuyi SA. 1992. The pattern of human intestinal helminth infections in farming communities in different parts of Ondo State, Nigeria. West Afr J Med. 11:13-7.
29. Amahmid O, Asmama S, Bouhoum K. The effect of waste-water reuse in irrigation on the contamination level of food crops by Giardia cysts and Ascaris eggs. Int J Food Microbiol. 49:19-26.
30. Perry MJ. 2003. Children's agricultural health: traumatic injuries and hazardous inorganic exposures. J Rural Health. 19:269-78.
31. Alexe DM, Petridou E, et al. 2003. Characteristics of farm injuries in Greece. J Agric Saf Health. 9:233-40.
32. The Vertical Farm Project – http://www.verticalfarm.com
33. Population Reference Bureau
34. Tilman D, Fargione J, et al. 2001. Forecasting agriculturally driven global environmental change. Science.

292: 281-284.
35. http://www.globalfundforchildren.org/index.htm
36. http://nutrition.tufts.edu/academic/hungerweb/
37. Goudriaan J, Zadoks JC. 1995 Global climate change: Modelling the potential responses of agro-ecosystems with special reference to crop protection. Environ Pollut. 87:215-24.
38. Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA. 2003. Fingerprints of global warming on wild animals and plants. Nature. 421:57-60.
39. Pimentel D. 1991. Global warming, population growth, and natural resources for food production. Soc Nat Resour. 4:347-63.
40. McMichael AJ. 2001. Impact of climatic and other environmental changes on food production and population health in the coming decades. Proc Nutr Soc. 60:195-201.
41. Abate T, van Huis A, Ampofo JK. 2000. Pest management strategies in traditional agriculture: an African perspective. Annu Rev Entomol.45:631-59.
42. http://www.cc.utah.edu/~ptt25660/tran.html
43. http://www.energy.gov/energysources/index.htm
44. Rebitzer G, Ekvall T, Frischknecht R, et al. 2004. Life cycle assessment part 1: framework, goal and scope definition, inventory analysis, and applications. Environ Int. 30:701-20.
45. Gunderson LH. 2000. Ecological resilience –in theory and application. Ann Rev Ecology Systematics. 31:425-439.
46. National Science Foundation Program in Long Term Ecological Research. (available online).
47. http://www.hubbardbrook.org/
48. Likens GE, Bormann FH. 1995. Biogeochemistry of a Forested Ecosystem. Second Edition, Springer-Verlag New York Inc. P. 159.
49. Likens GE. 2001. Ecosystems: Energetics and Biogeochemistry. pp. 53-88. In: Kress WJ and Barrett G (eds.). A New Century of Biology. Smithsonian Institution Press, Washington and London.
50. Bernhardt ES, Likens GE. 2002. Dissolved organic carbon enrichment alters nitrogen dynamics in a forest stream. Ecology. 83:1689-1700.
51. Likens GE, Bormann FH, Johnson NM, D. W. Fisher, Pierce RS. 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed-ecosystem. Ecol. Monogr. 40:23-47.
52. Fundamnetals of Ecolog. Eugene P. Odum and Gary W. Barrett. Thomson Brooks/Cole, Pubs. Australia, Canada, United States. 2005.
53. Ragossnig AM, Lorber KE. 2005. Combined incineration of industrial wastes with in-plant residues in fluidized-bed utility boilers--decision relevant factors. Waste Manag Res. 23:448-56.
54. Lugwig C, Hellweg S. 2002. Municipal solid waste management. Strategies and technologies for sustainable solutions. Springer Verlag, Pub. Heidleberg, New York. P. 545.
55. Hewitt LM, Marvin CH. 2005. Analytical methods in environmental effects-directed investigations of effluents. Mutat Res. 589:208-32.
56. Khosla R, Bhanot A, Karishma S. 2005. Sanitation: a call on resources for promoting urban child health. Indian Pediatr. 42:1199-206.
57. Malkow T. 2004. Novel and innovative pyrolysis and gasification technologies for energy efficient and environmentally sound MSW disposal. Waste Manag. 24:53-79.
58. Stalnacke P, Vandsemb SM, Vassiljev A, Grimvall A, Jolankai G. Changes in nutrient levels in some Eastern European rivers in response to large-scale changes in agriculture. Water Sci Technol. 49:29-36.
59. Fawell J, Nieuwenhuijsen MJ. 2003. Contaminants in drinking water. British Medical Bulletin 68:199-208.
60. Foster SSD, Chilton PJ. 2003. Groundwater: the processes and global significance of aquifer degradation. Phil Trans: Biol Sci. 358: 1957-1972.
61. Holt MS. 2000. Sources of chemical contaminants and routes into the freshwater environment. Food Chem Toxicol. 38(1 Suppl):S21-7.
62. Ritter L, Solomon K, Sibley P, Hall K, Keen P, Mattu G, Linton B. 2002. Sources, pathways, and relative risks of contaminants in surface water and groundwater: a perspective prepared for the Walkerton inquiry. J Toxicol Environ Health A. 65:1-142.
63. Cairns, Jr., John. 2000. Sustainability and the future of humankind: two competing theories of Infinite Substitutability. Politics and the Life Sciences 1: 27-
64. So Human an Animal. Rene Dubos. Transaction Pub. United States, UK. 1968.
65. Teal JM. 1962. Energy flow in a salt marsh in Georgia. Ecology. 43:614-624.
66. Ricklefs RE. 2000. The economy of nature. WH Freeman & Co. 5th ed.