

# FOOD, ENERGY, AND SOCIETY

THIRD EDITION

DAVID PIMENTEL  
MARCIA H. PIMENTEL



CRC Press

Taylor & Francis Group

Boca Raton London New York

---

CRC Press is an imprint of the  
Taylor & Francis Group, an **informa** business

---

# Contents

List of Figures .....	xv
Preface .....	xvii
Authors .....	xix
<b>Chapter 1</b> Energy and Society .....	1
Development of Societies and Energy .....	2
Energy from Fire .....	2
Energy and the Structure of Societies .....	3
Food as a Focal Point of Societies .....	5
Use of Energy in Food Systems .....	6
References .....	7
<b>Chapter 2</b> Energy and Power .....	9
Energy and Work .....	9
Laws of Thermodynamics .....	9
Measures of Energy and Power .....	11
Biological Solar Energy Conversion in Agriculture .....	12
Renewable Biological Energy versus Fossil Fuel Energy .....	13
References .....	16
<b>Chapter 3</b> Solar Energy in Natural and Managed Ecosystems .....	17
Natural Ecosystems .....	17
Forest Ecosystems .....	19
Agricultural Ecosystems .....	20
Reference .....	20
<b>Chapter 4</b> Ecological Systems, Natural Resources, and Food Supplies .....	21
The Structure and Function of Ecosystems .....	21
Evolution of Living Systems .....	24
Biogeochemical Cycles .....	25
Aquatic Ecosystems .....	26
Terrestrial Ecosystems .....	27
Agricultural Ecosystems .....	28
Water .....	28
Nutrients .....	28
Pest Controls .....	29
Agricultural Ecosystem Stability .....	30
Species Diversity .....	30

Crop Yields .....	30
Annual versus Perennial Crops .....	31
Food Needs for Future Generations .....	32
Requirements for Solving Food Problems .....	32
Safeguarding the Environment .....	32
Science and Technology .....	33
Population .....	33
References .....	34
<b>Chapter 5</b> Manipulating Ecosystems for Agriculture .....	37
Ecosystems .....	37
Agriculture and the Natural Ecosystem .....	38
Biomass .....	39
Manipulating Agroecosystems .....	40
Interdependency of Factors in Crop Production .....	41
Energy, Labor, and a Standard of Living .....	43
References .....	44
<b>Chapter 6</b> Hunter-Gatherers and Early Agriculture .....	45
Hunters and Gatherers of Food .....	46
Early Agriculture .....	51
References .....	55
<b>Chapter 7</b> Early Livestock Systems and Animal Power .....	57
Early Animal Herding .....	57
Animal Power as an Energy Source .....	59
Animal Food-Consumption Patterns .....	63
Nutritional Quality of Protein Foods .....	65
References .....	66
<b>Chapter 8</b> Livestock Production and Energy Use .....	67
Animal Products Consumed in the U.S. Diet .....	67
Energy Inputs in Animal Product Production .....	68
Land Resources .....	70
Water Resources .....	71
World Food Needs .....	73
Conclusion .....	73
References .....	74
<b>Chapter 9</b> Energy Use in Fish and Aquacultural Production .....	77
<i>David Pimentel, Roland E. Shanks, and Jason C. Rylander</i>	
Ecological Aspects of Fish Production .....	77
Energy Efficiency of Fishery Production .....	79

Energy Efficiency of Ocean Fisheries .....	80
Northeast U.S. Fishery .....	80
U.S. Fishery .....	83
Peru .....	83
Gulf of Mexico and Australia .....	84
Malta .....	85
Adriatic .....	85
Marine Fisheries and the Environment .....	85
Management of Fishery Systems .....	86
Aquaculture .....	87
Conclusion .....	94
References .....	94
<b>Chapter 10 Energy Use in Grain and Legume Production .....</b>	<b>99</b>
Energy Inputs in Grain Production .....	99
Corn .....	99
Wheat .....	106
Oats .....	108
Rice .....	108
Sorghum .....	112
Energy Inputs in Legume Production .....	114
Soybeans .....	114
Dry Beans .....	115
Cowpeas .....	116
Peanuts .....	116
Agricultural Technology .....	116
References .....	118
<b>Chapter 11 Energy Use in Fruit, Vegetable, and                     Forage Production .....</b>	<b>121</b>
Fruits .....	121
Apples .....	121
Oranges .....	121
Vegetables .....	123
Potatoes .....	123
Spinach .....	123
Tomatoes .....	126
Brussels Sprouts .....	126
Sugar Beets .....	127
Cassava .....	128
Forage Production .....	129
Alfalfa .....	129
Tame Hay .....	130
Corn Silage .....	132
Vegetarianism and Nonvegetarianism and Energy Inputs .....	133
References .....	135

<b>Chapter 12</b>	<b>Energy Inputs in Crop Production in Developing and Developed Countries</b>	<b>137</b>
	<i>David Pimentel, Rachel Doughty, Courtney Carothers, Sonja Lamberson, Nirali Bora, and Katherine Lee</i>	
Introduction		137
Food and Population		137
World Energy Resources		138
Methodology		139
Energy Inputs and Economic Costs for Major Crops		140
Corn		141
Wheat		143
Rice		144
Soybeans		145
Potatoes		147
Cassava		149
Sweet Potatoes		149
Cole Crops		151
Tomatoes		151
Oranges		151
Apples		151
Irrigated Crops		152
Economics of Food Crop Production		152
Changes in World Food Crop Production		153
Fossil Energy Use and Crop Yields		153
Fossil Energy Use in Crop Production		154
Renewable Energy		154
Future Technologies		155
Summary		156
References		156
<b>Chapter 13</b>	<b>Environmental and Economic Costs of the Application of Pesticides Primarily in the United States</b>	<b>161</b>
Public Health Effects		162
Acute Poisonings		162
Cancer and Other Chronic Effects		162
Pesticide Residues in Food		164
Domestic Animal Poisonings and Contaminated Products		164
Destruction of Beneficial Natural Predators and Parasites		166
Pesticide Resistance in Pests		168
Honeybee and Wild Bee Poisonings and Reduced Pollination		169
Crop and Crop Product Losses		170
Ground- and Surface Water Contamination		172
Fishery Losses		173
Wild Birds and Mammals		173
Microbes and Invertebrates		175
Government Funds for Pesticide Pollution Control		176

Ethical and Moral Issues .....	177
Conclusion .....	178
References .....	179

<b>Chapter 14</b> Water Resources: Agricultural and Environmental Issues .....	183
---	-----

*David Pimentel, Bonnie Berger, David Filberto, Michelle  
Newton, Benjamin Wolfe, Elizabeth Karabinakis, Steven Clark,  
Elaine Poon, Elizabeth Abbett, and Sudha Nandagopal*

Water Resources .....	184
Hydrologic Cycle .....	184
Availability of Water .....	184
Groundwater Resources .....	185
Stored Water Resources .....	186
Water Use .....	186
Human Water Use .....	186
Agriculture and Water .....	187
Water in Crop Production .....	187
Irrigated Crops and Land Use .....	188
Energy Use in Irrigation .....	188
Soil Salinization and Waterlogging in Irrigation .....	189
Water Runoff and Soil Erosion .....	190
Water Use in Livestock Production .....	191
Water Pollution and Human Diseases .....	191
Limits to Water Use .....	193
Costs of Water Treatment .....	193
Economic Costs of Water Subsidies .....	193
Loss of Biodiversity .....	194
Effect of Climate and Environmental Change on Water Availability .....	195
Conflicts over Water Use .....	195
Conserving Water Resources .....	196
Using Water Wisely in the Future .....	196
References .....	197

<b>Chapter 15</b> Soil Erosion: A Food and Environmental Threat .....	201
---	-----

Causes of Erosion .....	201
Soil Structure .....	203
The Role of Vegetative Cover .....	203
Land Topography .....	203
Other Soil Disturbances .....	203
Assessing Soil Erosion .....	204
Loss of Productivity in Managed Ecosystems .....	205
Worldwide Cropland .....	205
U.S. Cropland .....	205
Pasture and Range Land .....	206
Forest Land .....	206

Effects of Erosion on Terrestrial Ecosystems .....	207
Water Availability .....	207
Nutrient Loss .....	207
Soil Organic Matter .....	208
Soil Depth .....	208
Biomass and Biodiversity .....	209
Sediments and Wind Blown Soil Particles .....	211
Conservation Technologies and Research .....	212
Productive Soils and Food Security .....	212
References .....	214
<b>Chapter 16</b> Conservation of Biological Diversity in Agricultural, Forestry, and Marine Systems .....	221
<i>David Pimentel, Tsveta Petrova, Marybeth Riley, Jennifer Jacquet, Vanessa Ng, Jake Honigman, and Edwardo Valero</i>	
Causes of Reduced Species Diversity .....	222
Deforestation and Destruction of Natural Habitats .....	222
Soil Erosion and Salinization .....	223
Alien Biological Invaders .....	223
Chemical Pollutants .....	224
Marine Ecosystems and Aquaculture .....	224
Global Climate Change .....	225
Biological Diversity .....	225
Preservation of Biological Diversity—Large and Small Organisms .....	228
Biodiversity and Economic and Environmental Benefits .....	228
Plant, Animal, and Microbe Biomass and Diversity .....	229
Strategies for Conserving Biological Diversity .....	229
Plant Species Diversity .....	230
Intercropping .....	230
Shelter Belts and Hedgerows .....	231
Livestock Manure .....	232
Habitat Diversity .....	232
Agroforestry .....	232
Mixed Forests .....	233
Pasture Management .....	233
Pesticide Reduction .....	233
Conserving Fisheries .....	234
Protected Parks .....	234
Global Climate Change .....	235
Conclusion .....	235
References .....	236
<b>Chapter 17</b> Food Processing, Packaging, and Preparation .....	245
Food Processing .....	245
Canning .....	246
Freezing .....	247

Salting .....	247
Drying .....	247
Smoking .....	248
Various Processed and Prepared Foods .....	249
Packages for Foods .....	251
Cooking and Preparing Foods .....	252
References .....	254
<b>Chapter 18</b> Transport of Agricultural Supplies and Foods .....	257
Transport of Agricultural Supplies and Goods to the Farm .....	257
Transport of Food and Fiber Products from the Farm .....	258
References .....	258
<b>Chapter 19</b> Renewable Energy: Current and Potential Issues .....	259
<i>David Pimentel, Megan Herz, Michele Glickstein, Mathew Zimmerman, Richard Allen, Kratina Becker, Jeff Evans, Benita Hussan, Ryan Sarsfeld, Anat Grosfeld, and Thomas Seidel</i>	
Hydroelectric Systems .....	260
Biomass Energy Systems .....	262
Wind Power .....	263
Solar Thermal Conversion Systems .....	264
Solar Ponds .....	264
Parabolic Troughs .....	265
Photovoltaic Systems .....	265
Hydrogen and Fuel Cells .....	266
Passive Heating and Cooling of Buildings .....	267
Geothermal Systems .....	268
Biogas .....	268
Biofuels: Ethanol, Methanol, and Vegetable Oil .....	269
Transition to Renewable Energy Alternatives .....	270
Conclusion .....	271
References .....	272
<b>Chapter 20</b> Biomass: Food versus Fuel .....	277
<i>David Pimentel, Alan F. Warneke, Wayne S. Teel, Kimberly A. Schwab, Nancy J. Simcox, Daniel M. Ebert, Kim D. Baenisch, and Marni R. Aaron</i>	
Biomass Resources .....	277
United States .....	277
Brazil .....	279
India .....	282
Kenya .....	283
Biomass Energy Use .....	284



Conversion of Biomass to Ethanol, Biogas, and Heat .....	284
Ethanol .....	284
Fuelwood and Other Solid Biomass Fuels .....	288
Biogas .....	289
Biogas for Small Landholders .....	291
Socioeconomic Factors .....	293
Brazil .....	293
United States .....	296
Environmental Impacts .....	297
Soil Erosion Problems in Biomass Systems .....	297
Nutrient Losses and Water Pollution Associated with Biomass Energy and Erosion .....	300
Air Pollution .....	301
Off-Site Environmental Effects from Biomass Harvesting and Erosion .....	302
Conclusion .....	303
References .....	303
 <b>Chapter 21 Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybean and Sunflower .....</b>	 311
<i>David Pimentel and Tad W. Patzek</i>	
Ethanol Production Using Corn .....	311
Energy Balance .....	312
Environmental Impacts .....	317
Negative or Positive Energy Return? .....	318
Food versus Fuel Issue .....	319
Switchgrass Production of Ethanol .....	319
Wood Cellulose Conversion into Ethanol .....	321
Soybean Conversion into Biodiesel .....	323
Sunflower Conversion into Biodiesel .....	325
Conclusion .....	327
References .....	328
 <b>Chapter 22 U.S. Energy Conservation and Efficiency: Benefits and Costs .....</b>	 333
<i>David Pimentel, Andrew Pleasant, Jason Barron,     Jen Gaudioso, Noah Pollock, Elisa Chae, Yoonji Kim,     Allison Lassiter, Christina Schiavoni, Alex Jackson, Melinda Lee,     and Andrea Eaton</i>	
Transportation .....	333
Passenger Vehicles .....	334
Freight Transportation .....	335
Buildings Sector .....	337
Heating and Cooling .....	337
Residential .....	337
Commercial .....	338

Equipment and Appliances .....	339
Residential .....	339
Commercial .....	340
Lighting .....	340
Residential .....	341
Commercial .....	341
Industrial Sector .....	342
Paper, Lumber, and Other Wood Products .....	342
Chemical Industry .....	344
Metals .....	345
Plastics and Rubber .....	346
Food Systems .....	347
Energy Subsidies .....	348
Oil Supply .....	349
Conclusion .....	350
References .....	350
 <b>Chapter 23 Summing Up: Options and Solutions .....</b>	 359
Future Food Needs .....	359
Population Health .....	359
Food Losses .....	361
Strategies for Meeting Food Needs .....	362
Energy Needs in Food Production .....	363
Land Constraints .....	364
Water Constraints .....	365
Climate .....	365
Environmental Pollution .....	366
The Future .....	366
References .....	367
 <b>Index .....</b>	 369