Chapter 2: Lithosphere

Resources

- Physical resources essential to sustain life are limited, with the exception of solar energy
- A sustainable economic system would operate without a net consumption of natural resources, i.e., the rates of resource use would equal or be smaller that the rates at which they are regenerated or re-cycled
- There are renewable and non-renewable resources

Non-renewable resources

- Non-renewable resources are present in finite quantity
- Extraction of resources: metals, fossil fuels, coal, etc. (development of new extraction tools)
- The recycling of resources is essential
- The use of alternative sources of energy (ex: use of biomass, solar panels, wind, etc.)

Easter Island (Rapa Nui)

- Remote island in S. Pacific
  - 1772, European explorers reached island, finding barren landscape, <2000 people
  - But evidence of sophisticated earlier civilization of ~30,000
  - **Resource over-exploitation**
    - Trees felled (statues, canoes)
      - →Top-soil erosion, lower freshwater (enhanced run-off), poorer crop yields
- Lessons for our planet?

Renewable resources

- Capable of being re-generated after harvesting, they could be used forever
- Ex: animals, plants, sols, water, solar energy
- A renewable source of energy can be degraded in the long term or contaminated or over-utilized (ex: Easter Island)

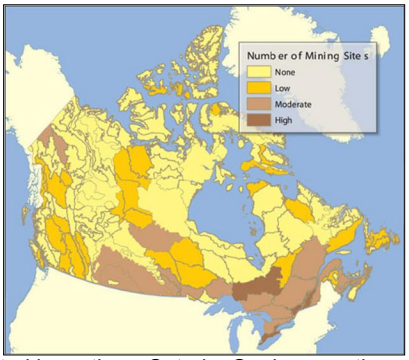
Resource management

- Crops, animal stocks, forests can be harvested sustainability with proper practices
  - Need to maintain a healthy environment
  - Need to maintain a good genetic diversity
  - Need to avoid over-exploitation
- Human factors can influence the size and productivity of natural resources

Mining & mineral processing

- Non-renewable resources
  - Metals, salts, rocks (granite, marble, etc.)
- Ore extraction technique can improve our recovery and extend the resources
- Essential for the economy of Canada and the world
  - 3.3% of GDP; 2.5% direct employed (2008)
- The mining industry creates jobs and infrastructure (roads, power lines, etc.)
- Often associated with major environmental problems

Mining activity in Canada

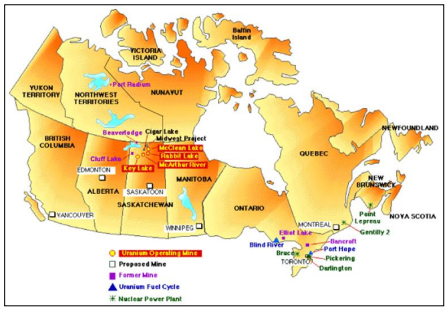


- Concentrated in northern Ontario, Quebec, southern SK/western MB

2.1 Mining activities

- Canada is one of the world's largest mineral exporters
- Large producer of:
  - Pb, Zn, Ni, Cu, Au (occur as **sulfides**)
    - Sudbury, Timmins (ON); Flin Flon (MB), Noranda (QC)
  - Chrysotile (asbestos)
    - Asbestos, QC
  - U
  - Potash
  - Diamonds

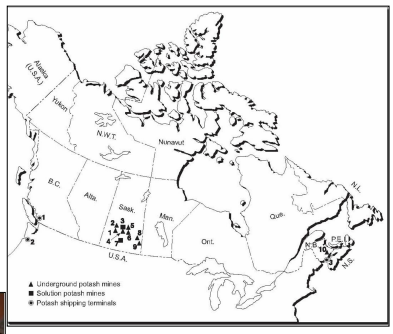
Uranium mining



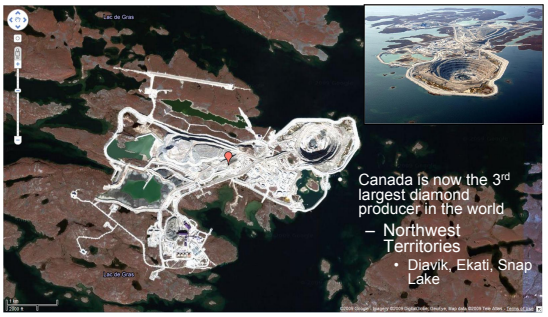
- World's leading producer
  - Northern SK (former mines in NWT & ON)

Potash mining

Largest in world
- Southern SK; western MB
- Largely used in fertilizer



Diamond mining



- Canada is now the 3rd largest diamond producer in the world
  - Northwest Territories
    - Diavik, Ekati, Snap Lake

Canada's reserves

- Apparent lifetime
  - Total metal reserve / metals produced from mine per year
  - Snapshot
- Depends on market price (esp. Au)
- Does not account for newly discovered metal ores or improvements in extraction/processing

Metal	Apparent life (y)
Ni	13
Cu	12
Au	9
Zn	9
Ag	6
Pb	5

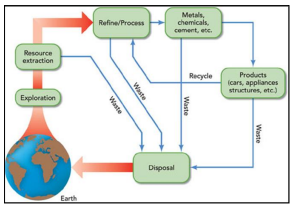
NRC, 2007

Recycling

- About 50% of the 15 million tons of iron and steel produced every year in Canada comes from recycled iron and steel scrap
- More than 90% of the lead consumed in Canada can be economically recycled
  - Secondary lead production represented approximately 60% of total Canadian refined lead production in 2008 (40% in 1995)
- Worldwide, lead production from recycled materials surpassed primary production for the first time in 1989

The Mining Processes

1. **Prospecting/exploration**
   - Water, soil sampling; exploratory drilling
2. **Mining/milling**
   - Crush rock, concentrate metal ore
   - Waste material termed **tailings**
3. **Smelting/processing**
   - Concentrated metal ore heated (roasting) or leached to extract metal
   - Many metal ores occur as sulfide minerals – heating produces SO_2 air pollution
4. **Post-operational**
   - Management of wastes (tailings), site remediation



Smelting: Pyrometallurgy

Roasting

$2M^{(+2)}\mathbf{S}^{(2-)}(s) + 3\mathbf{O}^{(0)}_2 = 2M^{(+2)}\mathbf{O}^{(2-)}(s) + 2\,\mathbf{S}^{(+4)}\mathbf{O}^{(2-)}_2(g)$
(high T)

where M is Ni, Zn, Pb, etc

Reduction

$M^{(+2)}\mathbf{O}^{(2-)}(s) + \mathbf{C}^{(0)}(s) = M^0(s) + \mathbf{C}^{(2+)}\mathbf{O}^{(2-)}(g)$
(high T)

where C is charcoal, coke

Hydrometallurgy

Leaching:

$2CuS(s) + 4H^+(aq) + O_2(g) = 2Cu^{2+}(aq) + 2S + 2H_2O$

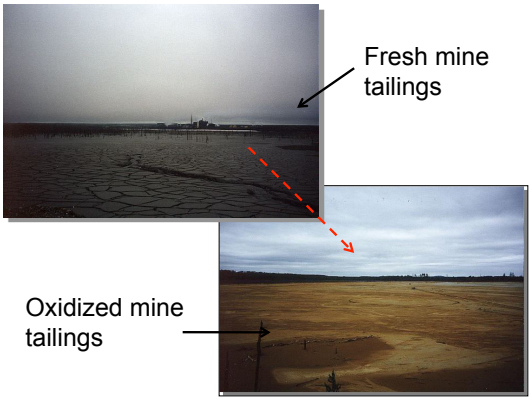
Reduction:

$2Cu^{2+}(aq) + 2H_2O = 2Cu(s) + O_2(g) + 4H^+(aq)$

- Metal (e.g. Cu) leached from ore (sulfide oxidized)
- Dissolved metal then reduced to metallic form and collected

Environmental impacts: Land

- Exploration requires temporary access to large tracts of land, ecosystem impacts are typically localized and short-term
- Milling and processing require much smaller tracts of land, but their impact in terms of tailings and waste rock disposal is much more significant and longer-term
- Existing and new mining facilities are now required to reclaim the land they disturb in accordance with government-approved reclamation plans
  - Of the total land area disturbed by mining, about 10% has been rehabilitated or re-vegetated to date



Rehabilitation of mining-impacted land

Geraldton, Ontario

1996/97 2000

Environmental impacts: Air

- Smelters require high operating temperatures and emit various pollutants directly into the local atmosphere
  - particulate matter, nitrogen oxides, sulfur dioxide, metals, and organic compounds
- Such substances may be deposited locally or transported over long distances
  - Heavy metals are deposited within 30 – 50 km stack
  - Acid deposition of SO_2, NO_x
    - Dry (as gases or particulates) and/or wet (rain, snow)
- Smelter facilities are located at Flin Flon & Thompson (MB), Sudbury & Timmins (ON), and Noranda (QC)

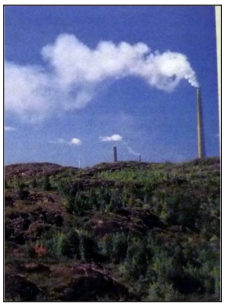
Acid deposition

Flin Flon, Manitoba

Acid deposition

- Queenstown, Tasmania, Australia
  - Large Cu smelter
  - "Moonscape"
    - Tourist attraction (!)

Lake St. Charles, Sudbury - rehabilitation

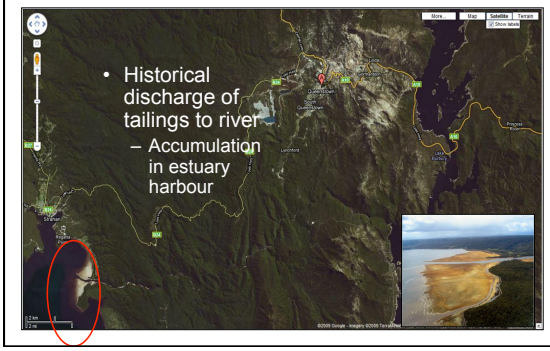


- Sudbury was once largest single source of SO_2 emissions in N. America (1969)
  - Emission reductions allowed vegetation to return

Environmental impacts: Water

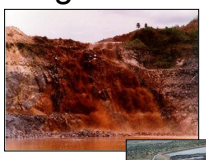
- Pollutants from:
  - Mine dewatering
  - Liquid effluents from the milling process
  - Surface water drainage and seepage from waste storage areas and inactive mines **(acid mine drainage)**
- Mine wastes are treated and stored on site. Untreated liquid effluents are normally released to the natural aquatic environment only when they meet strict environmental requirements; however, spills sometimes occur
  - E.g. breaches in tailings dams

Queenstown, Tasmania, Australia



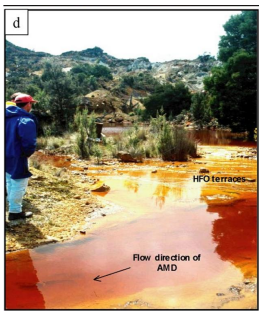
Impacts: Tailings dam breaches

- Spills caused by breaches in tailings dams
  - Omai gold mine (Guyana, 1995)
    - 3.2 million m^3 of cyanide tailings into adjacent river
  - Los Frailes Pb-Zn mine (Aznalcollar, Spain, 1998)
    - 4.5 million m^3 of metal-rich tailings into adjacent wildlife reserve
  - Baia Mare Au mine (Romania, 2000)
    - 0.1 million m^3 of cyanide tailings into river Danube



Acid mine drainage

- The most serious problem facing the mining industry in Canada
- Exposure of metal sulfides (e.g. pyrite FeS_2) in mine tailings and waste rock may generate acid mine drainage
  - Acidic waters rich in dissolved metals
- Controlling acid mine drainage is extremely difficult
  - Major challenge for the mining industry
    - Especially for abandoned mines



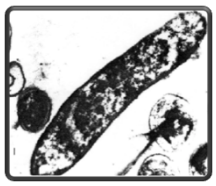
Acid mine drainage

(1) Oxidation of sulfide:

$$FeS_2 + 3\frac{1}{2}\,O_2 + H_2O \rightarrow Fe^{2+} + 2\,SO_4^{2-} + 2\,H^+$$

(2) Oxidation of iron: $Fe^{2+} + \frac{1}{4}\,O_2 + H^+ \rightarrow Fe^{3+} + \frac{1}{2}\,H_2O$

- Abiotic Fe^{2+} oxidation is very slow at low pH
- Acidophilic microorganisms can catalyze Fe^{2+} oxidation by several orders of magnitude
  - *Acidothiobacillus ferroxidans* is the most important of such bacteria



Acid mine drainage

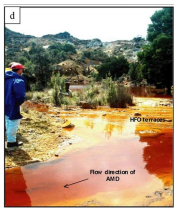
- The Fe^{3+} formed may precipitate:

$$Fe^{3+} + 3\,H_2O \rightarrow Fe(OH)_3(s) + 3\,H^+$$

- Or become an oxidant of FeS_2:

$$FeS_2 + 14\,Fe^{3+} + 8\,H_2O \rightarrow 15\,Fe^{2+} + 2\,SO_4^{2-} + 16\,H^+$$

  - **Positive feedback**



Contaminants associated with AMD

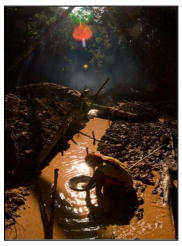
- **Organic** compounds
  - Base metal milling commonly uses a flotation process, whereby chemicals are mixed with ore in water solutions to separate the desired mineral from the ore
  - Flotation reagents used in base metal concentrators may include kerosene, organic flotation agents, and sulfuric acid. Residual reagents can be found both in the effluents from a mill and in stored tailings

Contaminants associated with AMD

- **Cyanide**
  - Gold mines are the major users of cyanide, which is employed in the milling process
  - Cyanide and cyanide–metal compounds may be removed from gold mill effluent either by natural degradation or by a treatment process, prior to discharge
- **Heavy metals**
  - Effluents from metal mines can contain As, Cd, Cu, Fe, Pb, Ni, Zn at various concentrations. All of these can have harmful effects on downstream aquatic life, especially fish
    - May also contain Hg (e.g. alluvial gold mining)

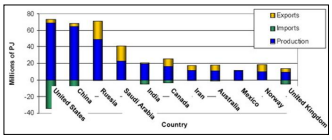
Case study: Au in Amazon basin

- Soaring gold price in late 1970's prompted gold rush in South America
- Alluvial sediments in Amazon basin panned for gold
- Use Hg for gold extraction (Hg adheres to Au, forming amalgam)
- Hg driven off by evaporation
  - "Mad hatter"
- Annual discharge of Hg to Amazon ecosystem estimated at 100 tonnes

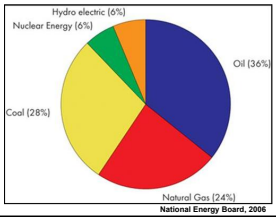


2.2 Energy

- There are many energy sources in the world, but most of them are produced in industrialized countries
- Many sources of energy are non-renewable, such as hydrocarbons (fossil fuels)
- Dependence on fossil fuels



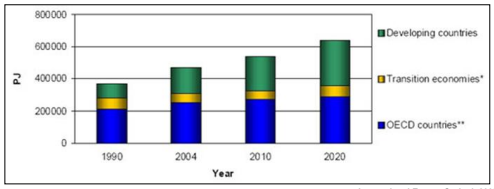
Sector sustainability tables, Govt. of Canada, 2007



National Energy Board, 2006

Energy demand – worldwide outlook

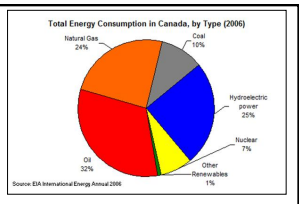
- Most energy consumption also occurs in industrialized countries
- World energy demand is growing (~1.6%/year)
  - Most growth will come from emerging economies (e.g. China, India) as population, economy grows

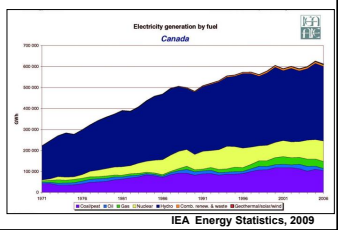


International Energy Outlook 2007

Energy supply - Canada

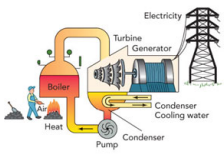
- Important sector of Canadian economy
  - 7.2% GDP, 2% directly employed
- Net exporter of energy
- Dominated by fossil fuels
- Electricity generation
  - Hydro, nuclear & fossil



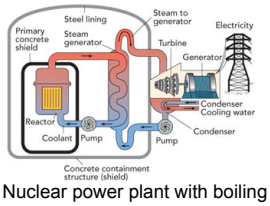


IEA Energy Statistics, 2009

Energy production



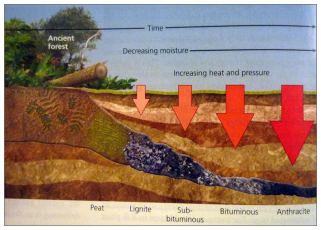
Fossil fuel power plant

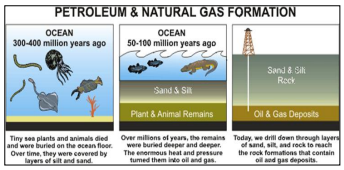


Nuclear power plant with boiling water reactor

Hydrocarbons (fossil fuels)

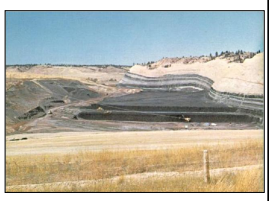
- Coal
  - Organic matter deposited on land, buried, T&P ↑ with burial, form coal
- Oil (petroleum)
  - Analagous to coal formation, but marine environments
- Natural gas
  - **Thermogenic** (high T&P, with oil)
  - **Biogenic** (anaerobic microbial degradation of organic matter)
    - Shallow depths (e.g. landfill, swamps)





Coal

- Used since ancient times
  - E.g. Romans in Britain 200-300 A.D.
- Most abundant fossil fuel
  - China & USA top producers & consumers (60%)
- Subsurface mining (shafts)
- Near surface
  - Open pit
    - E.g. Alberta & BC
  - Strip mining
    - Prairies & NB



Big Horn mine, WY (USGS)

Natural gas

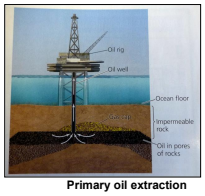
- Natural gas
  - Methane (CH_4)
  - Only recently become widely used
    - Energy, heating, cooking
  - "cleaner" burning
    - Lower CO_2 emission than coal or oil
  - Canada is world's 3rd largest producer (after Russia & US)
    - Offshore Atlantic Canada

Hibernia platform

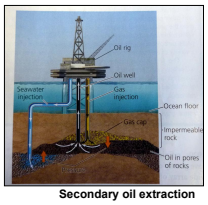
Oil (petroleum)

Oil brought to surface by:

1. Initial release of surround rock pressuring by tapping oil
2. Pumping
3. Water/gas injection (secondary extraction)

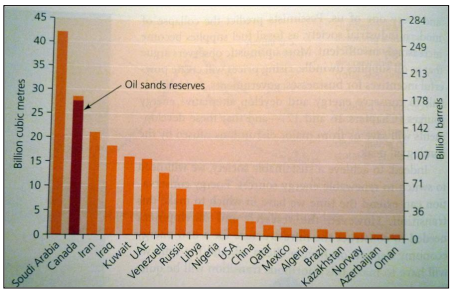


Primary oil extraction



Secondary oil extraction

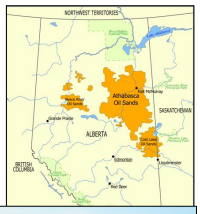
Worldwide oil reserves



- Middle East holds over half of world's proven oil reserves
- Canada has substantial oil reserves, but only produces 4% of world's oil

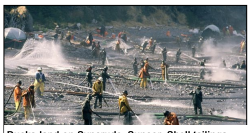
Oil/Tar sands

- Moist sand/clay rich in thick bitumen
- Massive deposits in Canada
  - Extracted by strip mining (too thick for conventional drilling)
- Costly to extract
  - ~$2 worth energy obtained per $1 invested!
  - ~$5 for conventional oil
  - Only economical recently



Environmental impacts of fossil fuel use

- Accidental spills (most visible form)
  - E.g. Exxon Valdez (1989), north Alaska
    - 10 million gallons
  - 1991 Gulf War (1991)
    - 42 – 460 million gallons
- Tar/oil sands mining
  - Contaminate local ecosystems
  - Oil ponds (similar to tailings ponds)



Ducks land on Syncrude, Suncor, Shell tailings ponds

230 dead birds counted so far at Syncrude's Mildred Lake facility

Last Updated: Tuesday, October 26, 2010 | 9:24 PM MT Comments:0700comment197

LRC/Alex

*Workers can be seen standing beside ducks lined up next to the Mildred Lake settling basin in northern Alberta on Tuesday. (Courtesy Edmonton Journal)*Just hours after the Alberta government announced that ducks had landed on a Syncrude tailings pond, officials said similar incidents had occurred at ponds belonging to Shell and Suncor.

Earlier Tuesday, the province announced that ducks were discovered on a tailings pond at Syncrude's Mildred Lake facility on Monday night. About 230 birds that had contact with bitumen floating on the surface had to be

Golf of Mexico, 2010

~4 million barrels of crude oil, cost: ~12 billion $

Kalamazoo river, 2010

Enbridge, 3.8 million liters in Kalamazoo river, USA

New-Zealand: October 2011

http://www.irishtimes.com/blogs/gallery/2011/10/12/oil-spill-off-new-zealand/

Accidental spills: contaminated soils

Environmental impacts of fossil fuel use

- Air pollution problems from fossil fuel combustion
  - Particulate matter (soot)
  - Acid deposition
    - SO_2, (esp. coal), NO_x
  - Toxic pollutants
    - Benzene
    - Mercury, arsenic (esp. coal)
- CO_2 emission
  - Driver of climate change
  - Gasoline (CH_2) combustion (automobiles etc)
  - Complete combustion: $CH_2 + 3/2\ O_2 = CO_2 + H_2O$

Carbon capture & storage

- Carbon **sequestration**
- From point sources (e.g. power plants, oil extraction rigs)
- Three general options
  1. Geological storage
  2. Ocean storage
  3. Mineral storage

CO_2 sequestration (from point sources)

- **Geological storage**: injection of CO_2 into porous rock formations:
  - Sedimentary basins
  - Depleted oil reservoirs and non economic coal beds
  - CO_2 also injected in oil reservoirs to improve petroleum recovery
  - There must be an impermeable cap rock above to prevent CO_2 from escaping
  - Such facilities exist in Norway and Canada, but so far they have only removed 0.01% of the global annual anthropogenic CO_2

CO_2 sequestration (from point sources)

- **Ocean storage:** injection of CO_2 at depths greater than 1000 meters where it is isolated from the atmosphere
- CO_2 would be dissolved in the oceans and be part of the global carbon budget
- However, it might cause a slight pH decrease of the water
- No know pilot scale project so far

CO_2 sequestration (from point sources)

- **Mineral carbonation:** Creation of stable minerals, such as calcite and magnesite, by reacting CO_2 with silicate minerals containing Ca and Mg (permanent sink)

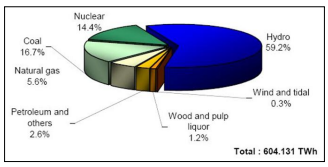
$$\underset{\text{(forsterite)}}{Mg_2SiO_4} + 2CO_2 = \underset{\text{(magnesite)}}{2\,MgCO_3} + \underset{\text{(quartz)}}{SiO_2}$$

$$\underset{\text{(anorthite)}}{CaAl_2Si_2O_8} + CO_2 + H_2O = \underset{\text{(calcite)}}{CaCO_3} + \underset{\text{(kaolinite)}}{Al_2Si_2O_5(OH)_4}$$

- It would require large industrial scale operations whereby silicates would have to be mined and crushed (*ex situ*)
- CO_2 could also be injected in basaltic rocks to form new carbonates *in situ* (slow kinetics)
- Some pilot studies (Iceland)

Renewable energy - **Hydroelectricity**

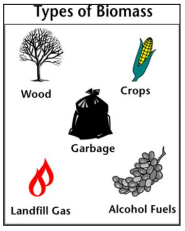
- It supplies ~60% of Canadian electricity
  - bulk of electricity in BC, MB, QC, NL
- It is **renewable**
- Cleaner than fossil fuels



- Either **storage** (reservoirs) or **river** uses
- Has limitations:
  - Dams and reservoirs can seriously alter aquatic ecosystems
    - Habitat destruction (e.g. Three Gorges, China), thermal pollution
  - Only so many naturally suitable lakes, or rivers amenable to damming
    - Increased public awareness of ecological impacts

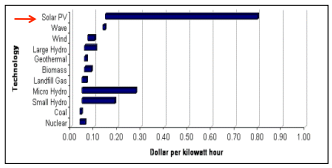
Renewable energy - **Biomass**

- **Biomass** energy
  - From Earth's plant life
    - Wood, peat, manure etc
    - Biofuels (e.g. ethanol from corn)
- Carbon neutral??
  - Much better than fossil fuels but not neutral
- Some problems
  - Deforestation → soil erosion
  - Increased price of food staple



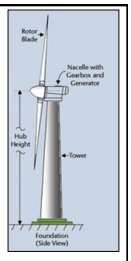
Renewable energy - **Solar**

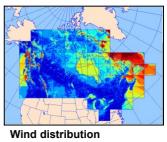
- **Solar** energy
  - Convert Sun's energy to electricity using photovoltaic cells
  - Expensive to produce
    - Costs diminish with take up



Renewable energy- **Wind**

- Fastest growing energy sector worldwide
- No direct CO_2 emissions (or SO_2, NO_x, heavy metals etc)
- (Few) drawbacks
  - Only works at certain wind speeds
  - Erratic power a problem
  - Threat to bats
  - Unsightly (?)

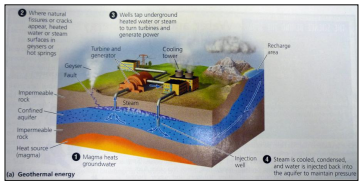




Wind distribution

Renewable energy - **Geothermal**

- Commonly exploited in certain geological settings
  - Tectonic plate margins (magma close to surface)
    - Hydrothermal systems
- Iceland, New Zealand, Japan, western USA

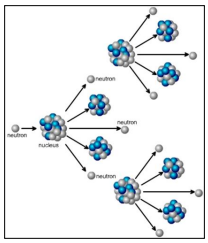


Renewable energy - **Tidal**

- Harness change in water level from tides
  - Sluice across tidal basin
    - Tide flows in, then trapped
    - Released at low tide, driving turbines
- Bay of Fundy
  - Greatest tidal difference in world
    - 16 m at head of bay!
  - One of only 3 tidal energy stations in world (Annapolis, NS)

Nuclear energy (fission)

- Supplies ~ 15% of Canada's electricity (but ageing reactors)
  - 50% in ON
- Harnessing forces that hold atomic nucleus together
- ^{235}U fuel rods bombarded with "slow" neutrons → ^{235}U breaks apart
  - Heat (steam for electricity generation)
  - Control rods slow chain reaction
    - controllable

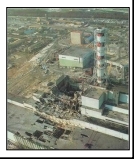


Nuclear energy (fission)

- CO_2 "free"
  - Attractive option to replace fossil fuels
  - But not without problems
- Waste management
  - Public acceptance for the disposal of nuclear fuel waste
- (Very small) possibility of accident with large consequences

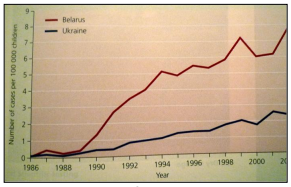
Nuclear "meltdown"

- Lots of heat generated by nuclear fission
  - Cooling essential
  - What happens if cooling halted?
    - "Meltdown"
    - Metal around nuclear fuel rods melts, releasing radiation
    - E.g. **Three Mile Island** (1979, PA; near miss, partial meltdown)
- Chernobyl
  - 1986, Ukraine (then USSR)
  - Explosion releasing radioactive material
    - ^{131}I, ^{137}Cs

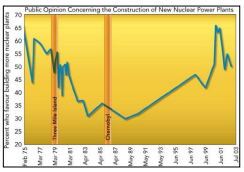


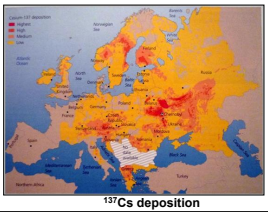
Impacts of Chernobyl

- 31 people killed directly
- >4000 cases of thyroid cancer (^{131}I)



Rates of child thyroid cancer





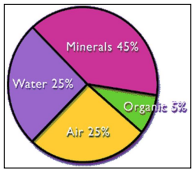
^{137}Cs deposition

Canada's energy portfolio

- Oil
  - Proven resources second only to Saudi Arabia
  - Primarily in the form of oil sands
- Natural gas
  - World's 3rd largest producer & 2nd largest exporter
- Uranium
  - Largest producer of uranium in the world
- Hydroelectricity
  - Second largest producer of hydroelectricity
  - Significant undeveloped potential
- Renewables
  - Large land area & coastline suit exploitation of solar, wind (and perhaps wave) energies

2.3 Soils

- Important natural resource
  - Supports diverse ecosystems
  - Agriculture
- Composed of minerals, organic matter, water & air
  - Colour
    - brown black (rich in o.m.)
    - white gray (poor in o.m.)
    - orange (rich in Fe)
- Formed from
  - **Weathering** of underlying bedrock
  - **Erosion**
  - Deposition & decomposition of **organic matter**

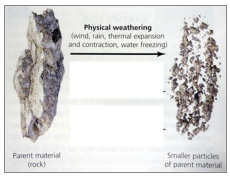


Weathering

- The physical breakdown and chemical alteration of rocks and minerals at the Earth's surface

Three types:

1. **Physical** (mechanical) weathering
   - Physical disintegration of rock
   - No chemical change
2. **Chemical** weathering
   - Interaction with atmosphere/ hydrosphere etc changes chemical make up of the rock
3. **Biological** weathering
   - Living things break down parent material by physical or chemical means



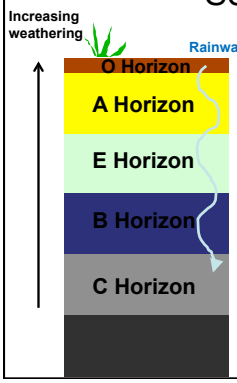
Chemical weathering

- Primary agent of chemical weathering is water (and oxygen)
  - Also CO_2, SO_2, NO_x, organic matter
- Mineral dissolution:

$CaCO_3 + 2H^+ = Ca^{2+} + H_2O + CO_2$ (g)
(calcite)

$2NaAlSi_3O_8 + 2H^+ + H_2O = Al_2Si_2O_5(OH)_4 + 4SiO_2 + 2Na^+$
(Na-feldspar) (clay) (silica)
(albite)

Soil profile



Thin layer – mostly **organic matter** (**OM**)

Topsoil – inorganic minerals, OM and partly decayed OM (**humus**)

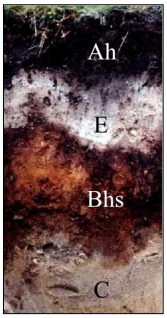
Leached zone – mineral grains remaining from dissolution, low OM

Accumulation zone – minerals & OM leached from A horizon accumulate here

Course rock – large rock particles only slightly weathered from underlying bedrock

Bedrock

Real soil profile



ISRIC - World Soil Information

Topsoil – inorganic minerals, OM and partly decayed OM (**humus**)

Leached zone – mineral grains remaining from dissolution (e.g. quartz) , low OM

Accumulation zone – minerals (e.g. oxides of Fe & Al) & OM leached from A horizon accumulate here

Course rock – large rock particles only slightly weathered from underlying bedrock

Soil texture

International	USDA
Gravel > 2 mm	> 2 mm
Sand 0.02-2 mm	0.05-2 mm
Silt 0.002-0.02 mm	0.002-0.05 mm
Clay < 0.002 mm	< 0.002 mm

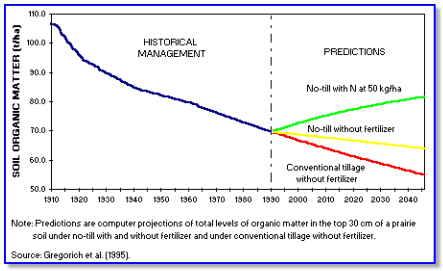
Agriculture: a renewable source

- Healthy crops: risk of infections, pathogens
  - Addition of pesticides
- Good soil quality
  - Addition of nutrients, fertilizers
- Problems of over-exploitation, contamination and erosion

Physical erosion

- The amount of organic matter in soil varies widely, from 1–10% in most agricultural soils to more than 90% in wetlands where peat is accumulated.
- Erosion of soil by wind and water is considered the most widespread soil degradation problem in Canada, especially in the Prairie provinces.
- Recent research suggests that losses of soil organic matter in Canada's un-eroded agricultural soils since initial cultivation are typically in the 15–30% range
- The amount of organic matter taken out of the soil in the form of crops is replenished by adding crop residues, manure and commercial fertilizers

Soil organic matter levels under three management practices



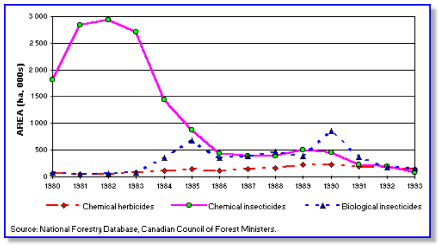
Note: Predictions are computer projections of total levels of organic matter in the top 30 cm of a prairie soil under no-till with and without fertilizer and under conventional tillage without fertilizer.

Source: Gregorich et al. (1995).

Pesticides, herbicides, insecticides

- Insecticides are used for insect control, primarily against Spruce Budworm and Hemlock Looper, and herbicides are used against competing vegetation
- Agriculture accounts for 80% of total sales, whereas domestic and industrial users account for the remaining 18%.
- From 1982 to 1993, the area of insecticide treatment fell from 3 million hectares to 256 000 ha, reflecting a decline in Spruce Budworm populations.Two-thirds of the area treated in 1993 involved the use of the biological insecticide Bt (*Bacillus thuringiensis*).

Trends in pesticide use in forest management in Canada,1980–1993



Source: National Forestry Database, Canadian Council of Forest Ministers.

Contaminants cont'd

- Contamination of soil by heavy metals (e.g., cadmium, lead, zinc) is a concern because metals are persistent and may affect plant, animal and human health
- Heavy metals enter agricultural soils primarily through atmospheric deposition and application of soil amendments such as fertilizers, animal manures, and sewage sludge, which is applied to agricultural land as a source of organic matter and nutrients