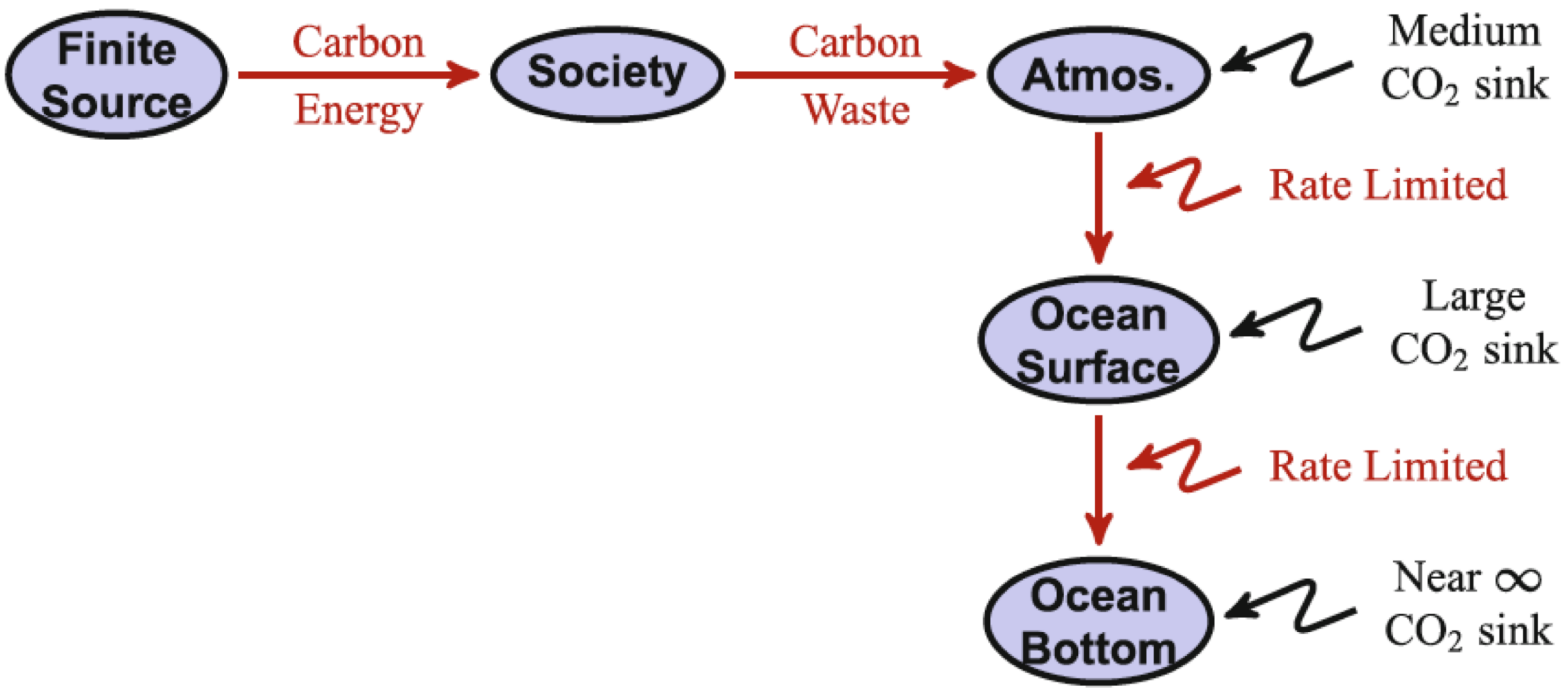
Global warming is the warming of the earth's climate caused by an increase in the concentrations of carbon-dioxide and methane gases in the atmosphere, due to human industry, fossil fuel consumption, and land use.

Suppose we begin with a rather naïve model of atmospheric carbon:

Human society, as a system, interacts with the rest of the world through the boundaries of the system. The naïve model has simplistically assumed fixed boundary conditions, that the sources (energy) and sinks (carbon pollution) are infinite, implying that humans do not influence the global climate.

A more realistic model, but also more complicated, understands energy sources and carbon-dioxide sinks to be finite, and therefore subject to influence by human activity:



So we cannot understand a system, such as a human society, in the absence of the *interactions* that the system has with others around it, such as how rapidly or easily carbon can flow from one place to another.

An additional subtlety is that the latter model is implicitly time-dynamic: there are *rates* of carbon transfer, and a continual transfer of carbon into a finite system implies a system which changes over time.

Two time-dynamic changes associated with carbon are indisputable:

1. CO_2 concentrations in the atmosphere are increasing over time, from 315 ppm in 1960 to around 400 ppm today;
2. Since 1800 the world's upper oceans have increased in acidity by 0.1 pH point, corresponding to a 30 % increase in acidity, due to the uptake of CO_2 into the ocean and the formation of carbonic acid

On the other hand, when we try to articulate questions of global warming, or any other sort of climate change over time, the problem becomes much more slippery:

What Is Our Baseline? We know that the climate has always been changing, switching between epochs with and without ice ages, for example. Indeed, the earth's climate changes over time periods of all scales:

Tens of millions of years …	Tropical Jurassic (dinosaur) era
Tens of thousands of years …	Ice ages
Hundreds of years …	Medieval warming period (950–1250 AD), So-called little ice age (1550–1850 AD)
Years …	1930's dust bowl, El-Niña / El-Niño

So at what point in time do we actually *start* measuring, in order to know whether the earth is warming or not?

What Is Actually Warming? The atmosphere is well-mixed and relatively easy to measure, whereas the heat uptake patterns in the oceans and the ground are far more variable, depending on the presence of subsident currents in the ocean, or geothermal activity underground.

On the other hand, although land and ocean have a far greater mass than the atmosphere, it is primarily the upper surfaces of land and ocean which would be warming, only a small fraction of the total:

Atmosphere	$6 \cdot 10^{14}$ kg per metre at sea level,	$5 \cdot 10^{18}$ kg in total
Ocean	$3 \cdot 10^{17}$ kg per metre of depth,	$1 \cdot 10^{21}$ kg in total
Land	$4 \cdot 10^{17}$ kg per metre of depth,	Ill-defined total mass

Furthermore it is primarily the upper surfaces of land and ocean which are biologically active, and thus a warming of only this top sliver may produce a disproportionate ecological impact. So is *global warming* ...

1. a *physical concept*, a warming of the land-oceans-atmosphere in total, which can be measured as increases in global average temperature?, or
2. an *environmental concept*, a disturbance to ecological balance caused by the warming of some *part* of the land-oceans-atmosphere, where the localized warming may produce almost no impact on the global average temperature, and so must be assessed indirectly via some other measurement?

What Is Causing the Warming? The increase, over time, in human fossil-fuel consumption is well documented. Similarly the increase, over a similar period of time, in atmospheric CO_2 concentration has been accurately measured. However a *correlation*, a statistical relationship, between two events is not the same as *causation*, where one event can be said to cause another.

Measuring a correlation is an exceptionally simple statistical test, whereas causation requires a much deeper understanding. In the case of global warming we need to understand the carbon cycle: the industrial and natural global sources and sinks of carbon.

Systems and Boundaries

A *system* is most fundamentally characterized by the manner in which it interacts with its surroundings:

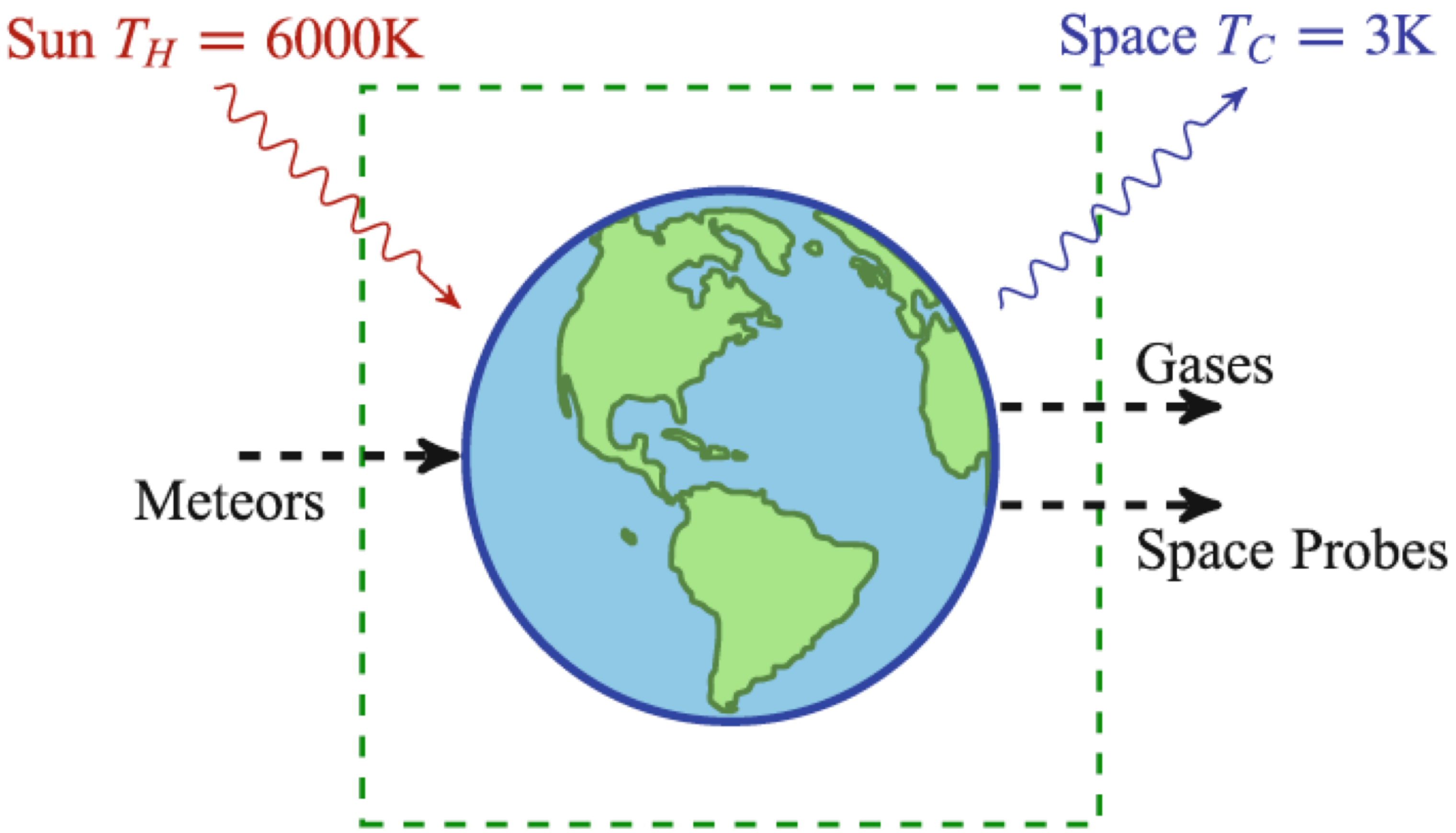
System type	Mass transfer	Energy transfer
Open system	✓	✓
Closed system	✗	✓
Isolated system	✗	✗

Open: Most human systems are open, since virtually all human societies and companies are based around trade and the exchange of goods.

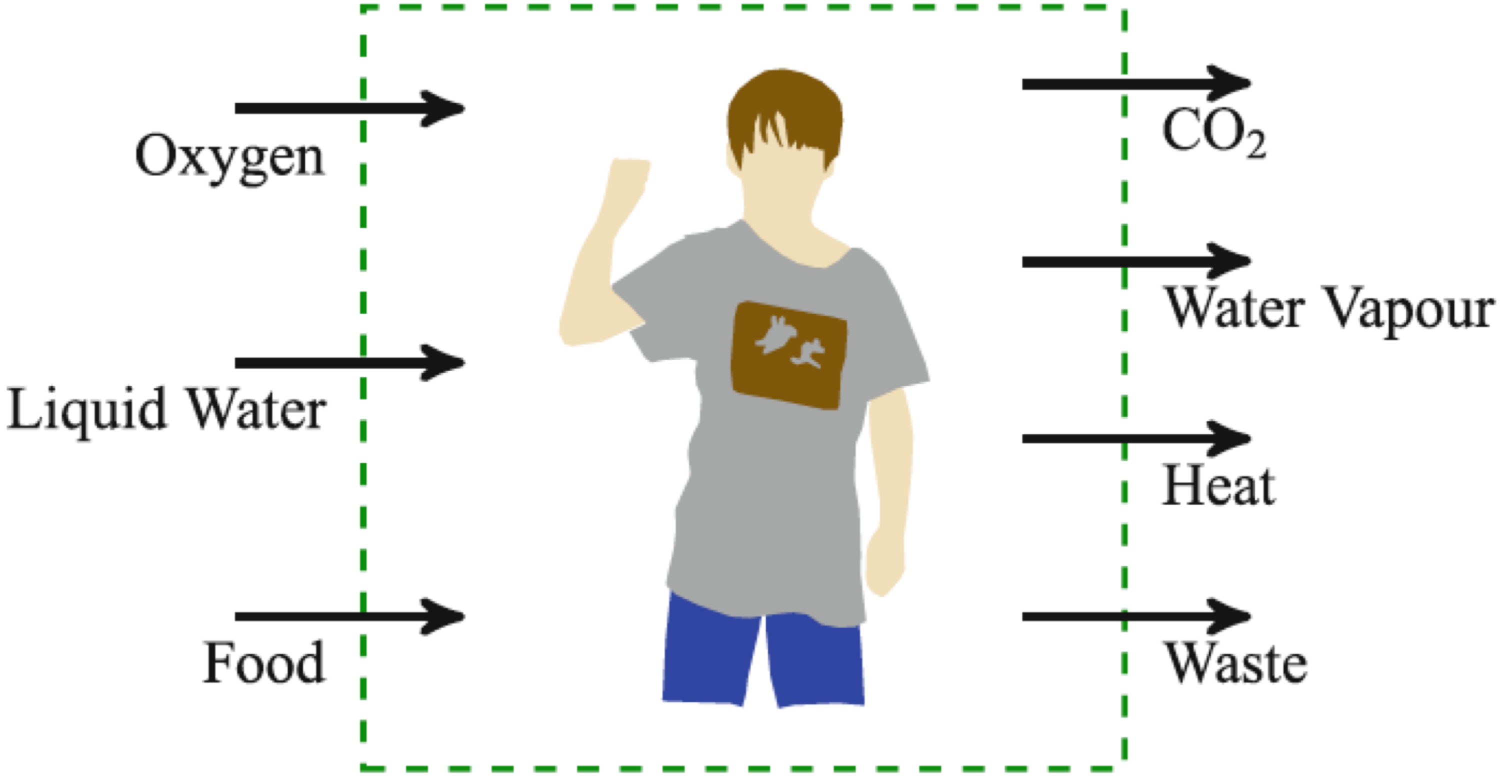
Closed: The earth as a whole is very nearly closed, since the inputs to the earth are dominated by solar energy (with a tiny amount of mass transfer from meteors), and the outputs from the earth are dominated by thermal energy (with a small amount of mass from the upper atmosphere and the occasional space probe).

Isolated: There are few, if any, isolated natural systems. Even a black hole is not isolated; to the contrary, it is quite open, since there can be substantial mass transfer into it. A well insulated, sealed test-tube in the lab would be close to being an isolated system.

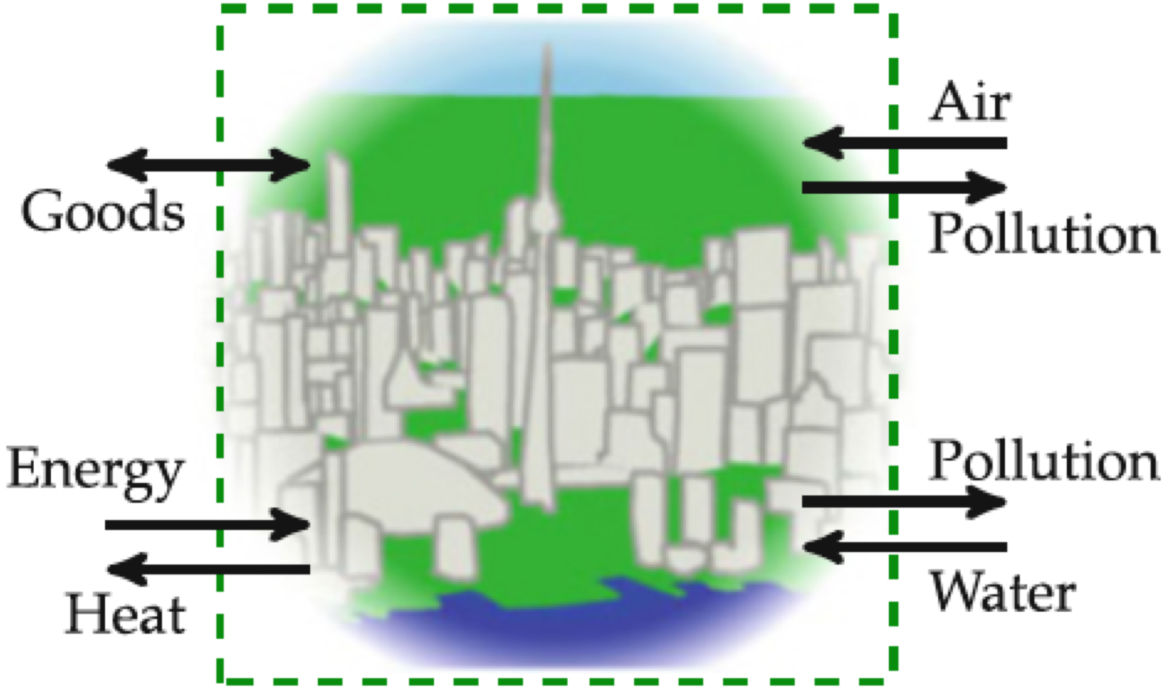
The earth is very nearly a closed system, primarily sunlight coming in and thermal energy going out, with only tiny changes in mass:



A single human is very much an open system, since food and water come into our bodies from outside of us. The goal in such a system diagram is to annotate the predominant interactions between a system and the outside world, not necessarily to be exhaustive and complete. Here, for example, we consider only movement of mass to/from a body, and not other interactions such as senses of touch, smell, sight, and hearing:



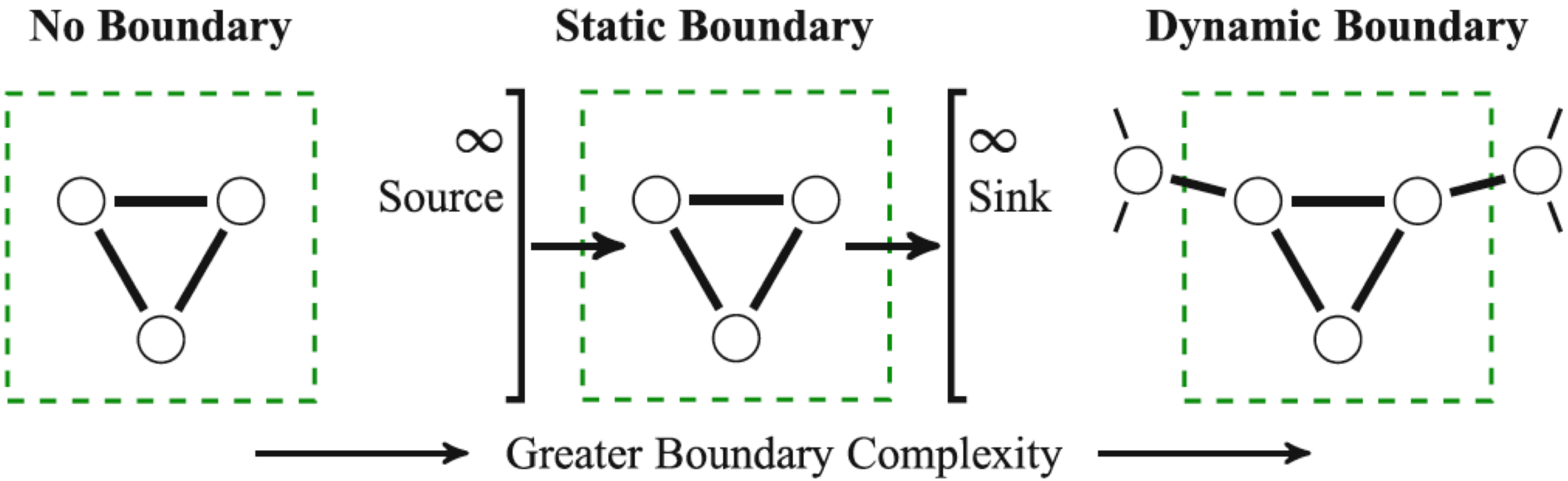
Human society is very open; indeed, the exchange of goods and trade is the hallmark of advanced societies. This diagram is terribly incomplete, as the range of materials coming into and out of a city is vast:

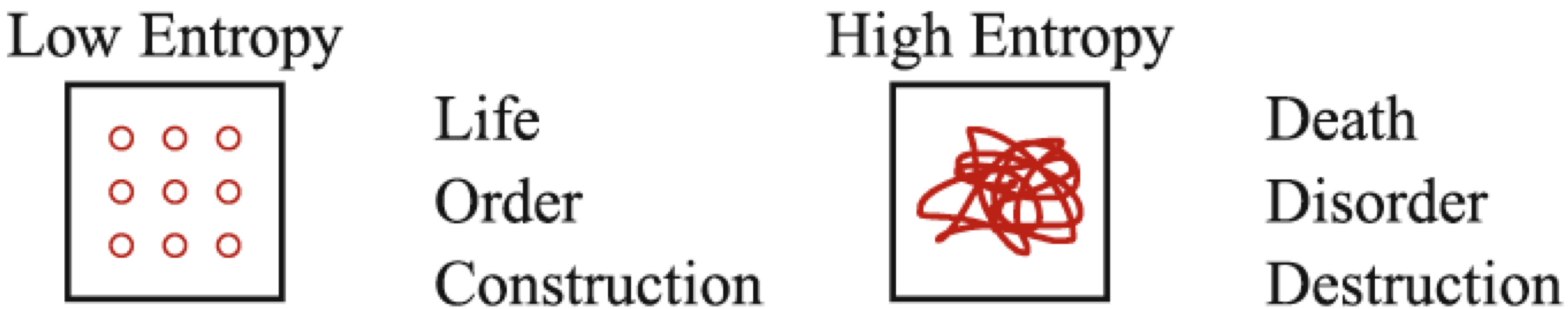


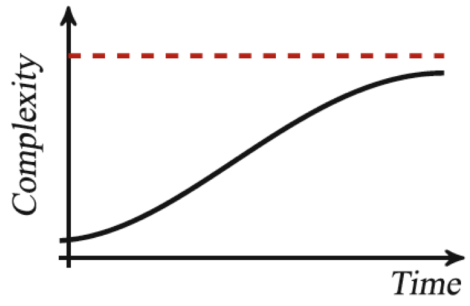
No Boundary: Isolated systems, with no interactions modelled outside of the boundary.

Static Boundary: Systems having infinite sources and sinks, meaning that the boundary conditions can simply be held fixed and are not influenced by the system in any way.

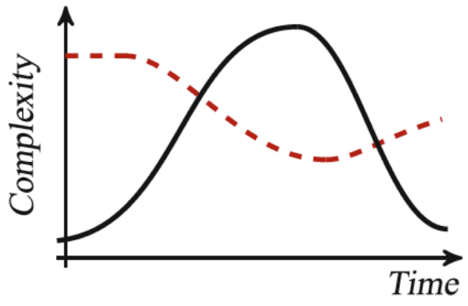
Dynamic Boundary: Systems having finite sources and sinks, external systems which can be affected by the modelled system.



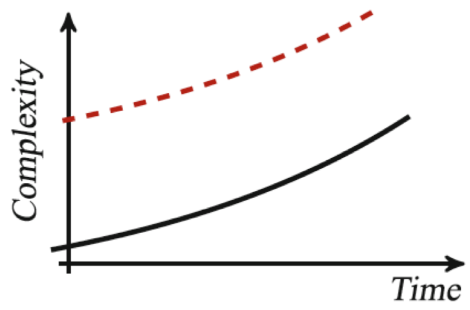




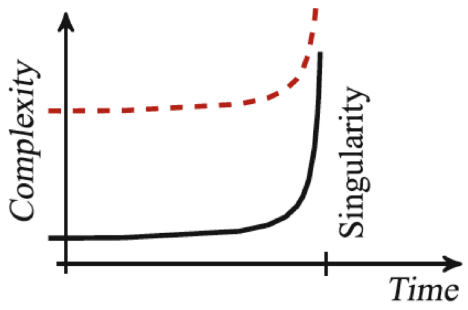
(Limited energy flow)
Logistic Model



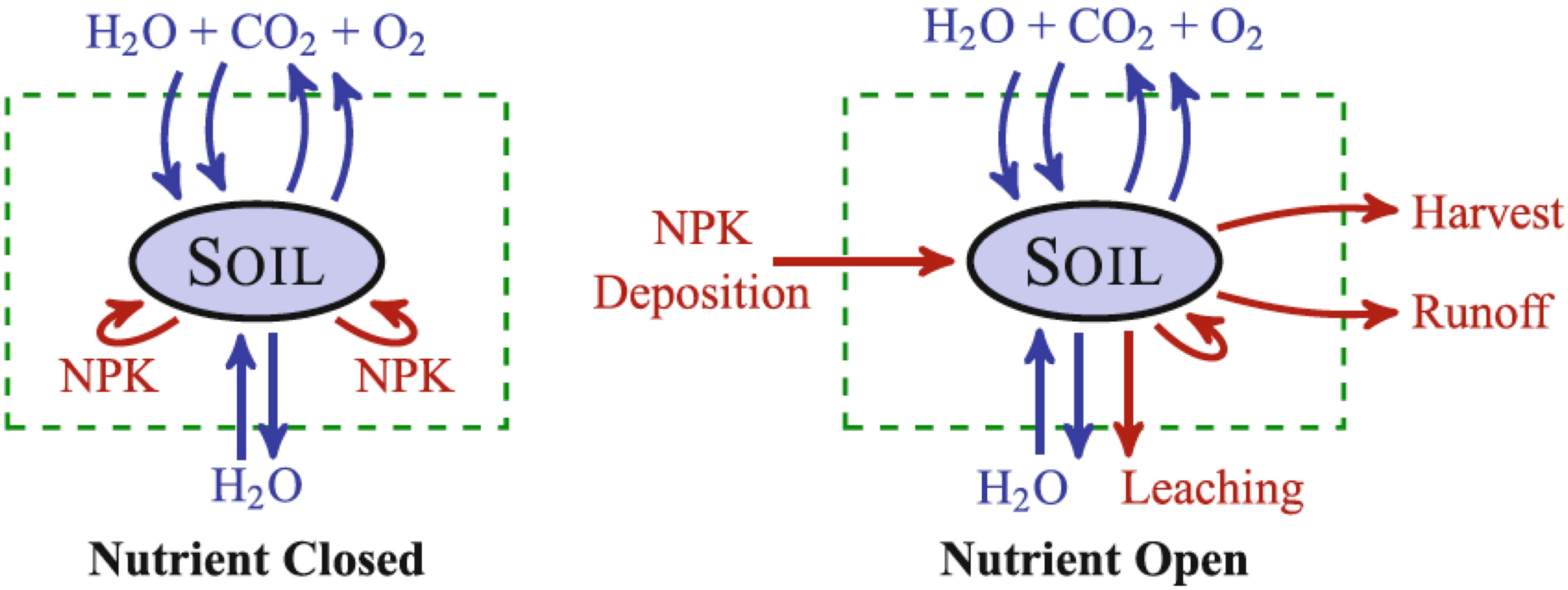
(Limit exceeded & eroded)
Predator-Prey Model



(Limits pushed via technology)
Indefinite-Growth Model

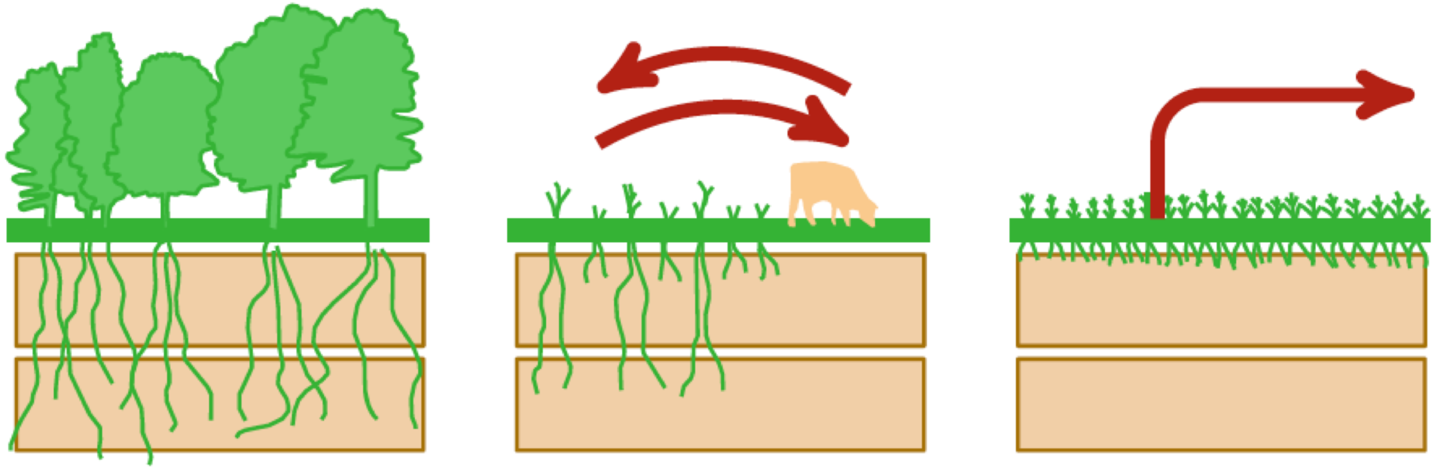


(Unlimited in finite time)
Singularity Model



Natural systems are nutrient-closed on human time scales, left. However most human influences, particularly logging, farming, and fishing, take a closed nutrient cycle and open it, right.

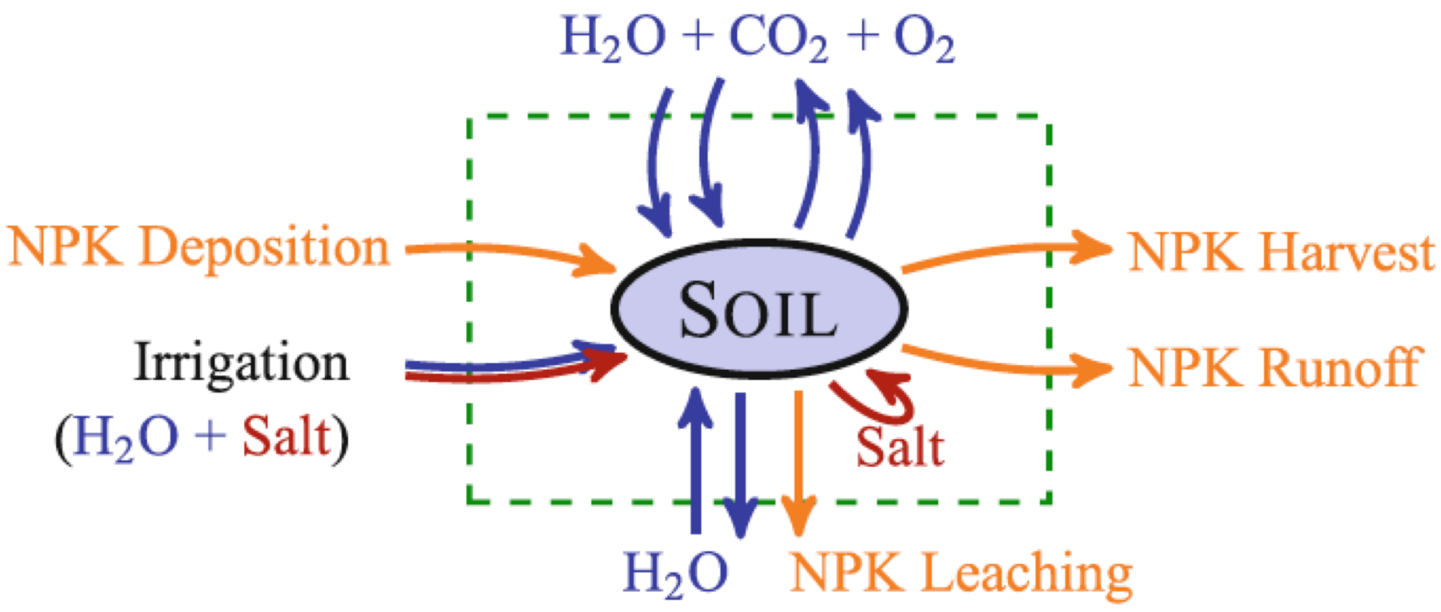
Mineral	Source	Mineral	Natural source	Modern source
C	Air	N	Lighting, bacteria, animals	Natural gas
H	Air/water	P	Soil weathering, volcanoes	Mining
O	Air/water	K	Soil weathering, volcanoes	Mining (potash)
Easy minerals		Difficult minerals		



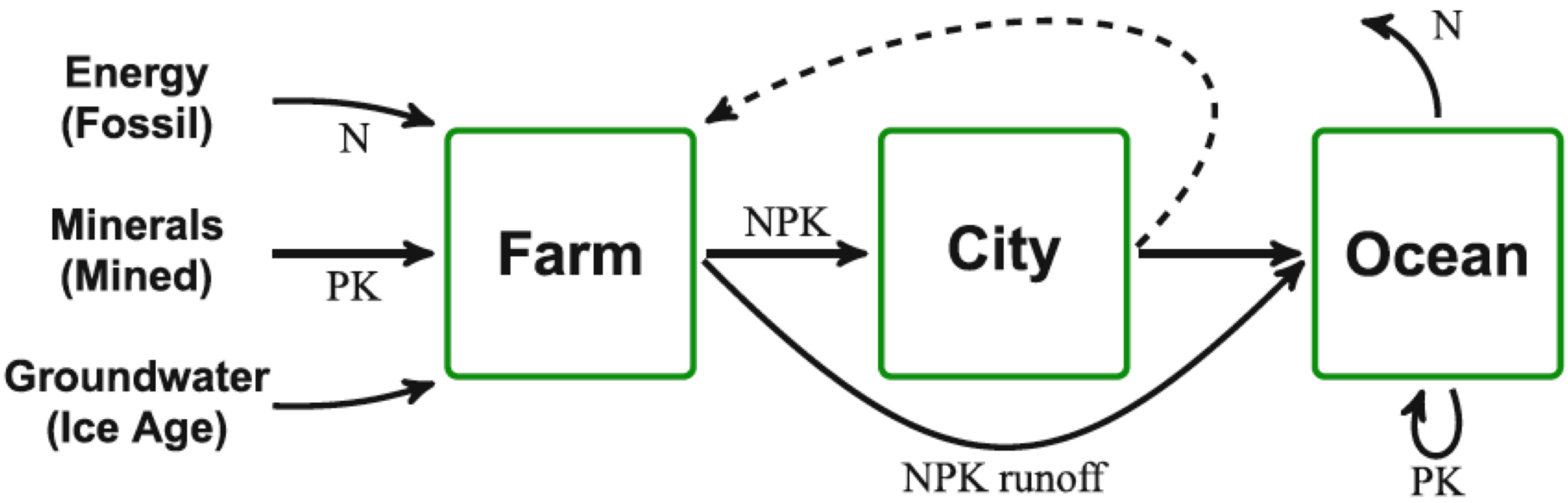
	Natural System	Traditional Agriculture	Modern Agriculture
Ecosystem:	Forest	Meadow	Row Crops
Plant Type:	Trees	Perennials	Annuals
Root Depth:	Deep	Deep	Shallow
Nutrients:	Locked up	Recycled	Exported
NPK Needs:	None	Modest	High

Mineral	Source	Mineral	Natural source	Modern source
C	Air	N	Lighting, bacteria, animals	Natural gas
H	Air/water	P	Soil weathering, volcanoes	Mining
O	Air/water	K	Soil weathering, volcanoes	Mining (potash)

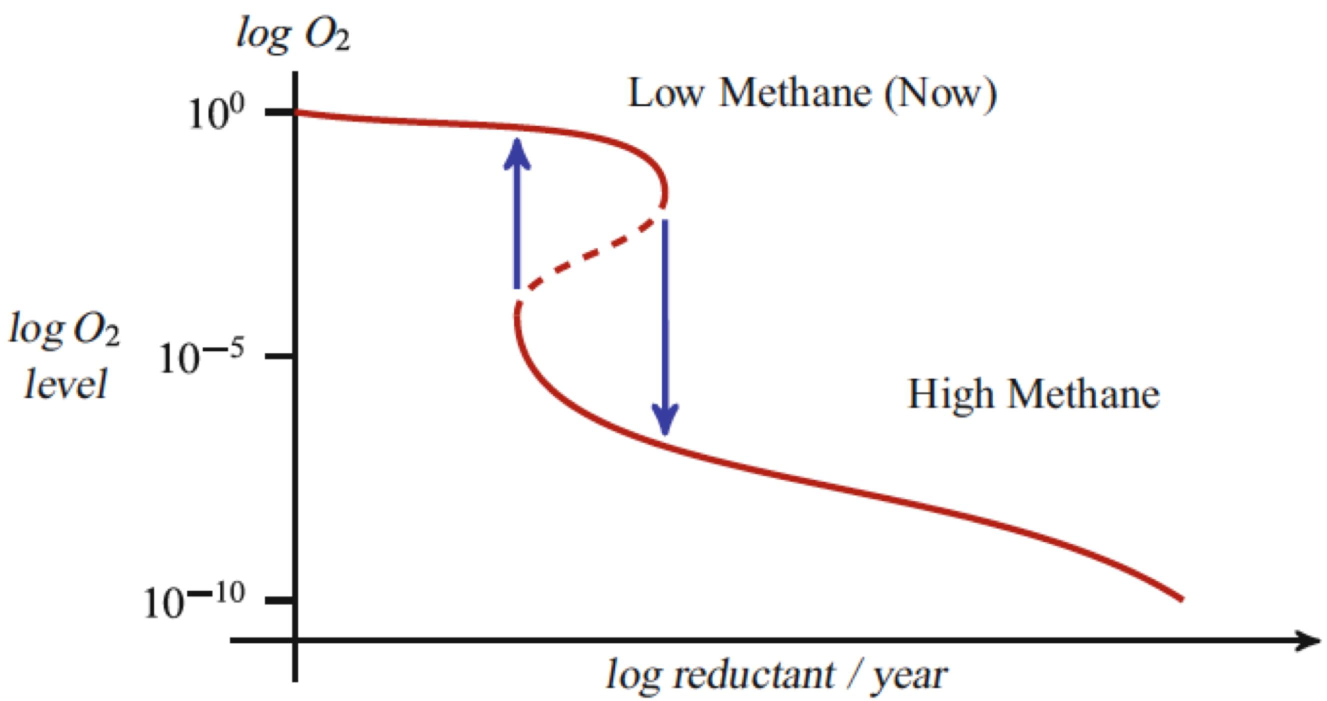
Easy minerals (C, H, O) — Difficult minerals (N, P, K)



System diagram for irrigated soil: treating a parcel of soil as a system allows us to see, in details, the flows across the system envelope. One pernicious issue is that of irrigation: groundwater contains dissolved salts which concentrate in the soil as the water evaporates but the salts do not. Over time this concentration can, depending on precipitation and groundwater patterns, lead to soil salination and a loss of productivity.



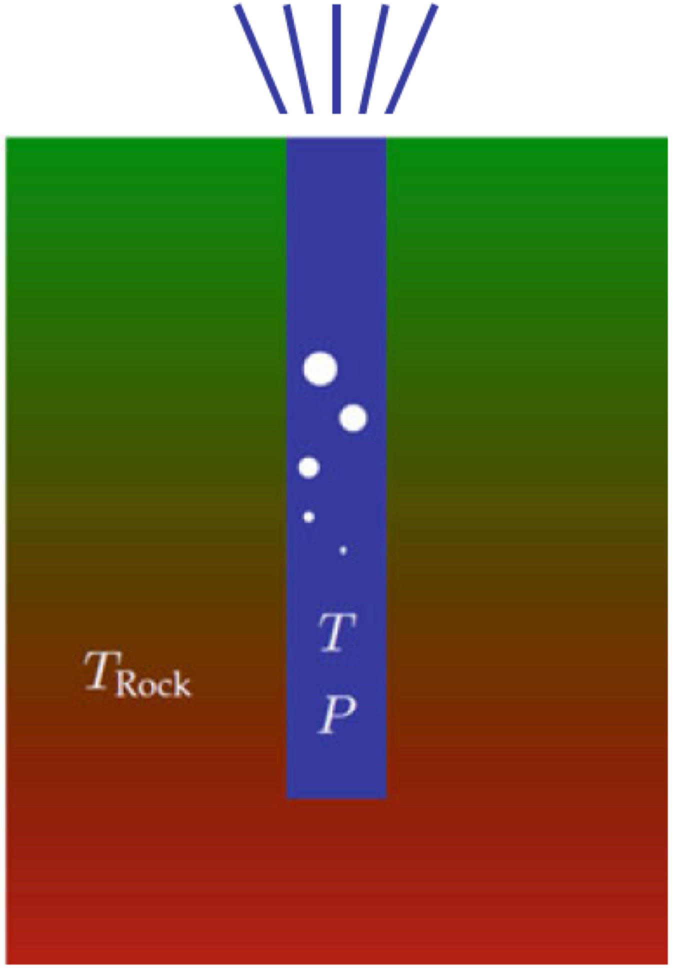
Modern nutrient flows: nutrients flows in Western societies are very much one-way: from mining/fossil sources, left, ultimately to the ocean, right. To the extent that mined nutrients are a finite source, this open approach is clearly unsustainable. The current exception to the one-way flow is the dashed arc, middle, representing a recycling of sewage back to farms.



Oxidation of the atmosphere: the oxygen levels in the atmosphere did not build up gradually, rather at some point *(the "Great Oxidation")* there was a catastrophic state transition to an atmosphere with much higher oxygen content. The horizontal axis measures the capacity for minerals to absorb (reduce) oxygen; what is of greater interest is the presence of a bi-stability, due to the presence/absence of an ozone layer.

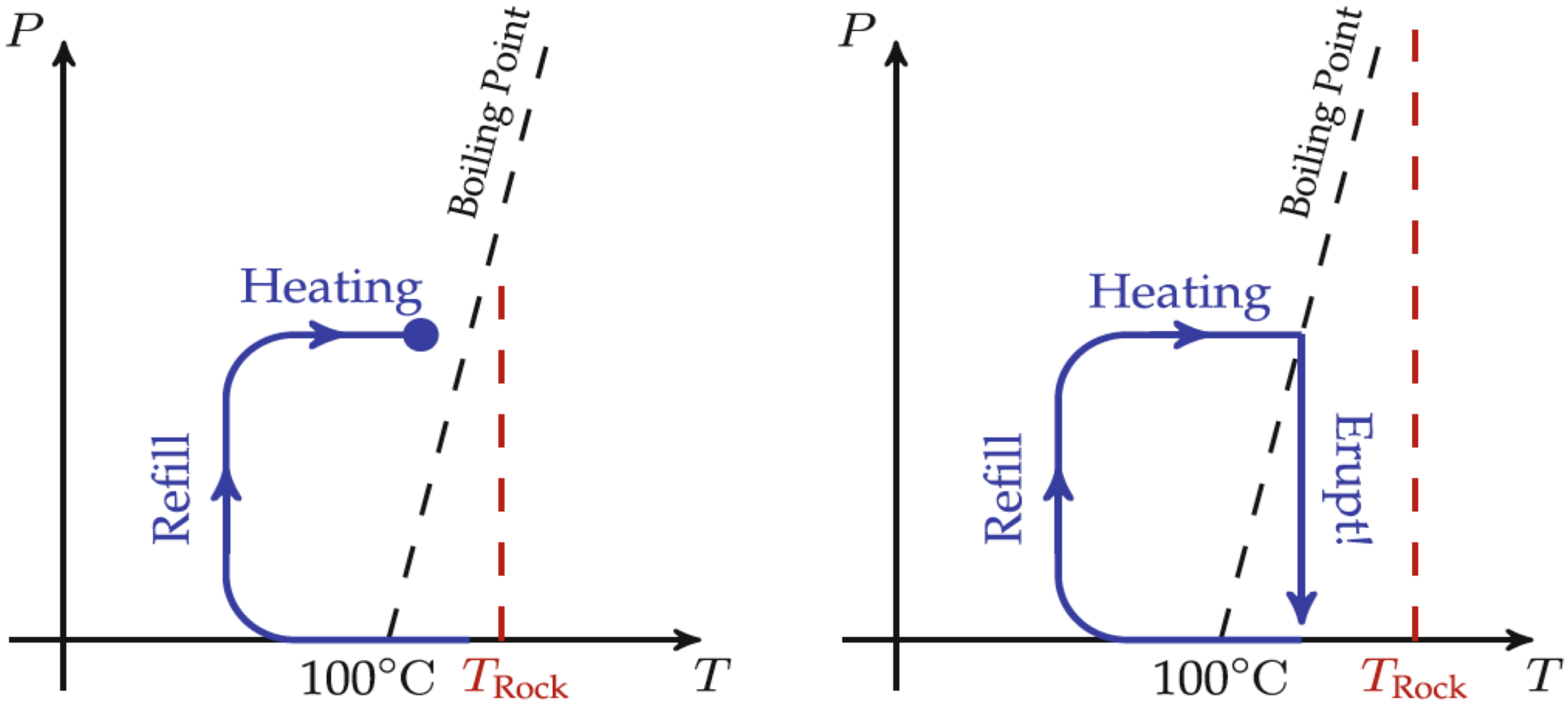
Adapted from C. Goldblatt et al., "Bistability of atmospheric oxygen . . . ," *Nature* (443), 2006.

(a) Geysir, Iceland



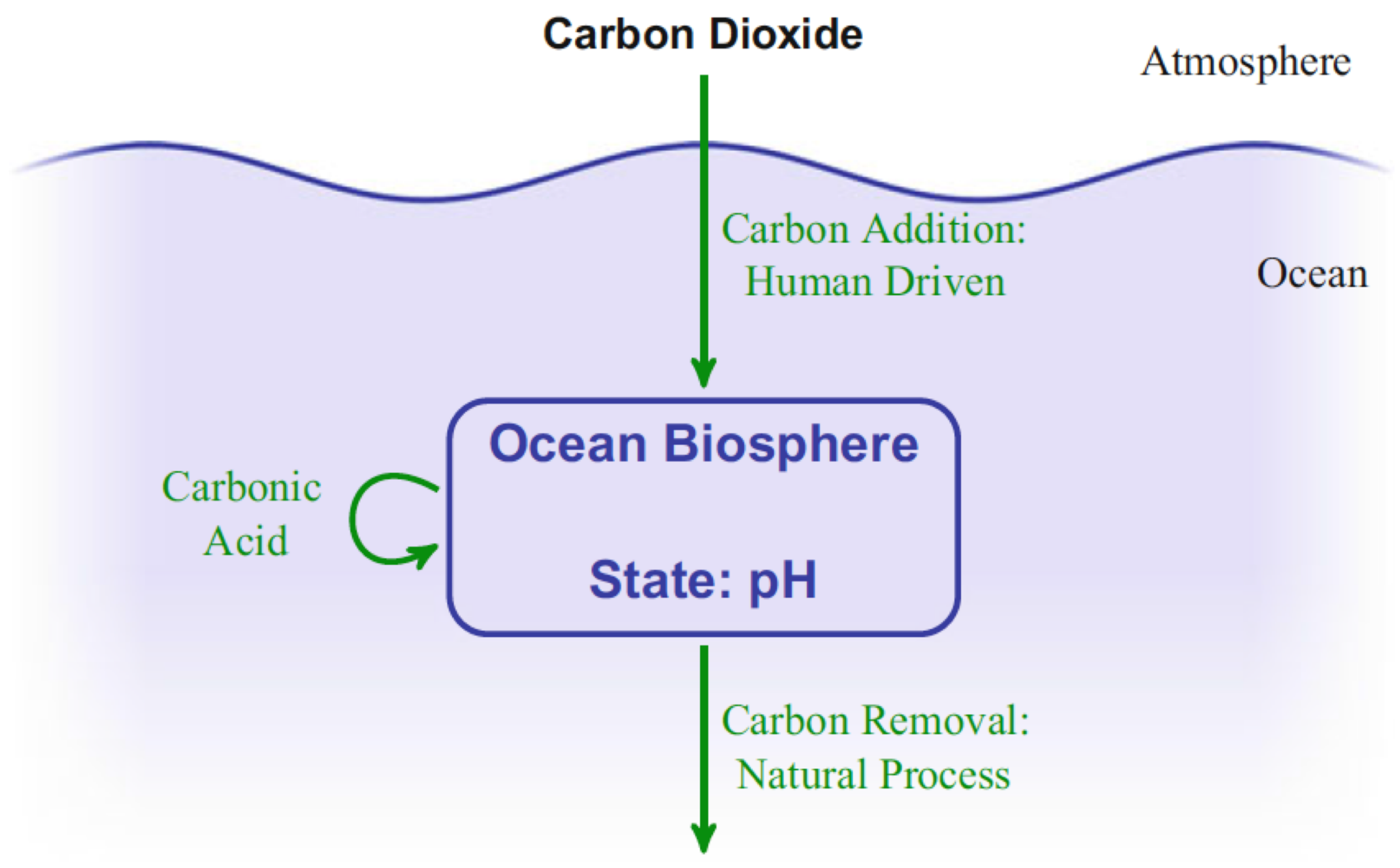
(b) Geyser profile and state

Geysers: the Geysir geyser, left, in Iceland erupts every few minutes. The geyser is formed as a deep channel, right, into which groundwater flows and is heated to the boiling point.

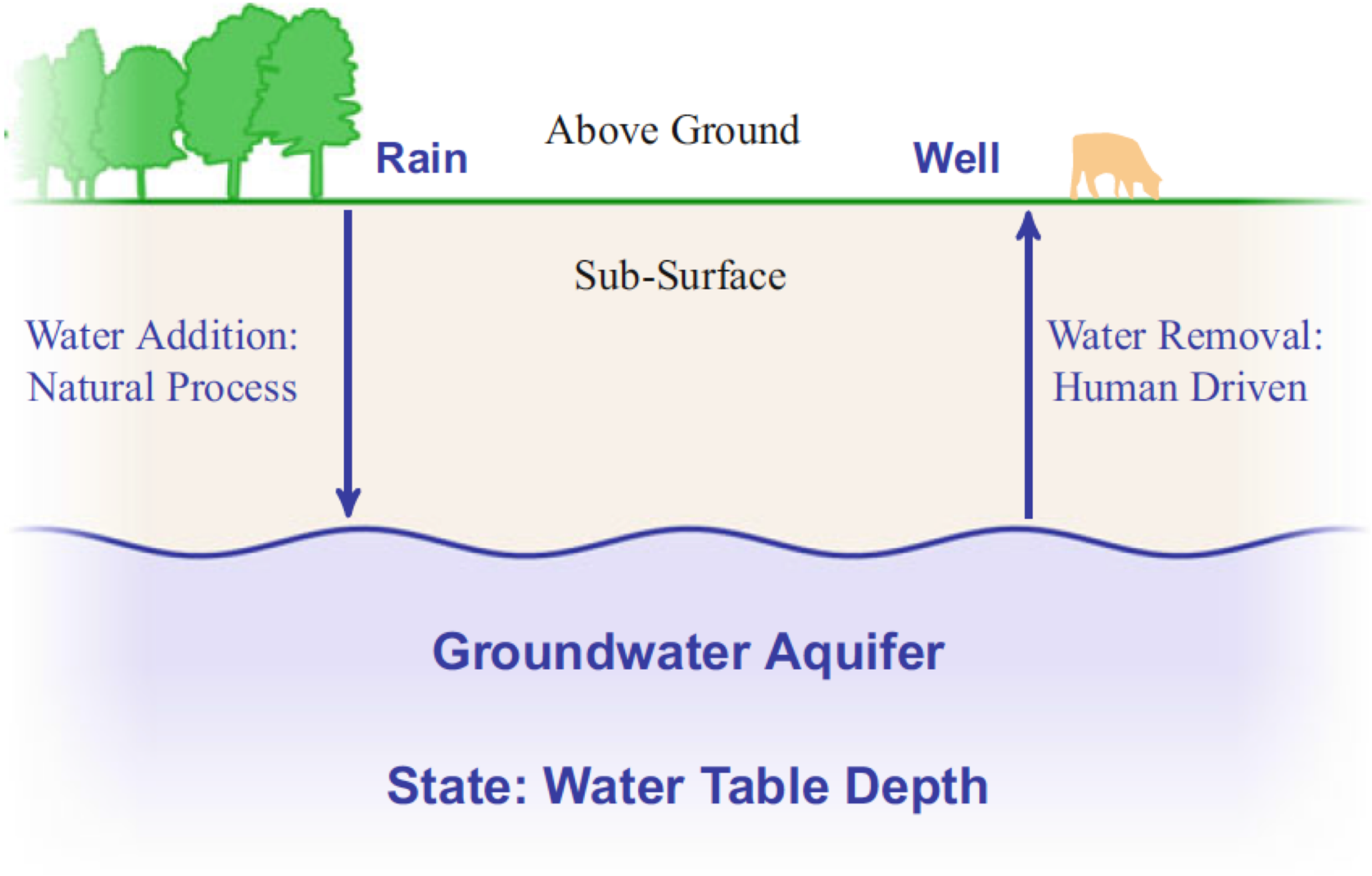


(a) Water channel in steady-state (b) Geyser system limit cycle

If the rate of heat flow into the water channel equals the heat flow lost by convection, then we have a stable fixed point and the system sits in steady state, *left*. However if the rock is sufficiently hot such that the local boiling point is exceeded, then we have a Hopf bifurcation to a limit cycle, right, leading to periodic eruptions.



Ocean acidification: the pH of the ocean is influenced by the rate at which CO_2 is absorbed from the atmosphere, relative to the rate at which CO_2 is sequestered to the deep ocean. The system is currently imbalanced, in that the input is controlled by human activities, whereas the output is not.



Groundwater system: humans control the rate of water removal, however the physics of subsurface water flow control the rate of water addition.