The succession-energy framework for reducing the environmental impacts of annual crop production

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Take home messages

1. Ecological succession theory and thermodynamics provide useful frameworks for conceptualizing agroecosystems

2. Annual cropping systems represent a state of perpetual early secondary succession

3. Maintenance of this successional state requires energy inputs, usually in the form of synthetic herbicides or physical disturbance

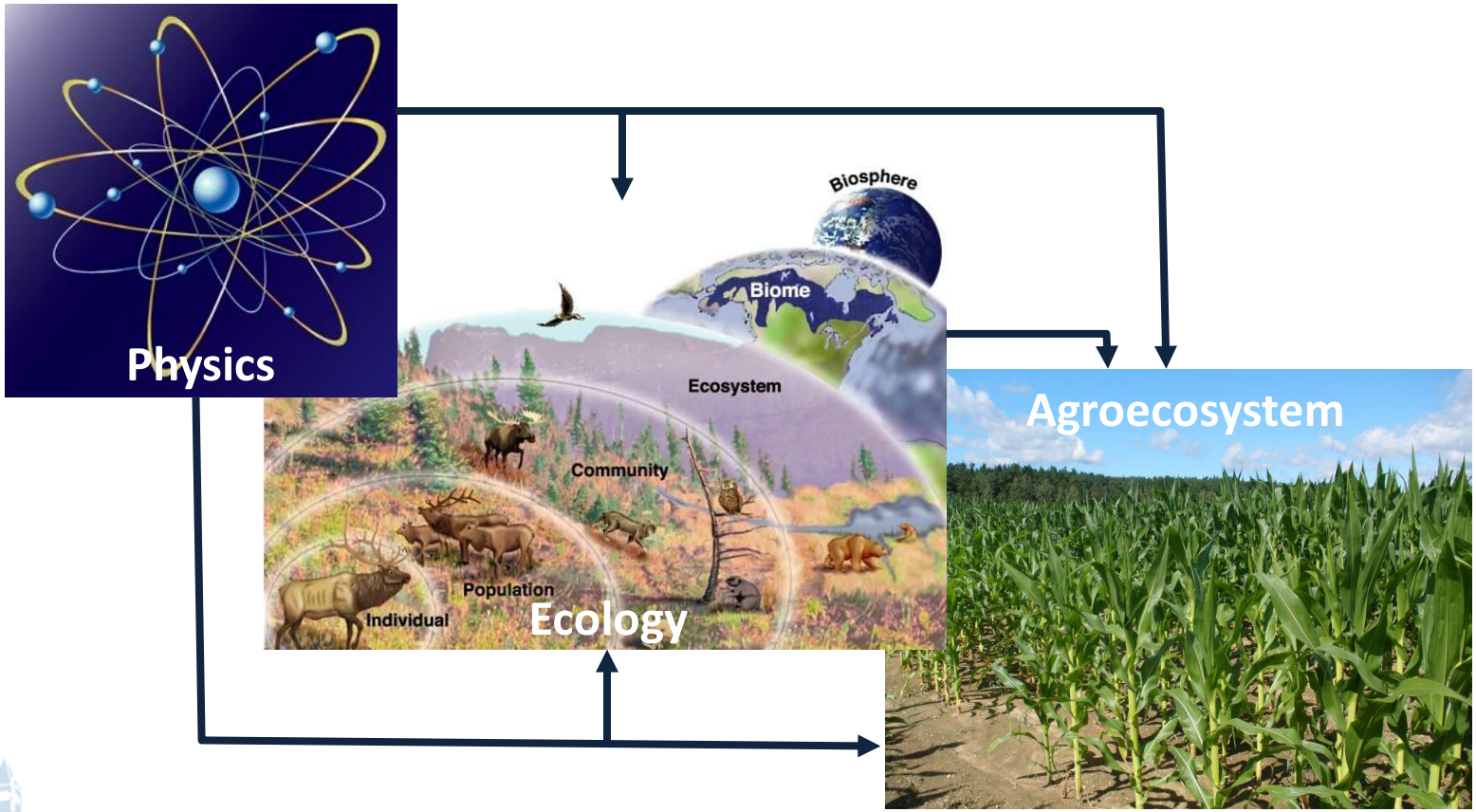
Take home messages

4. Under a succession-energy framework, the negative environmental impacts of weed control and fertilizer application are related to the amount of management energy required to maintain an area of soil in a state of initial secondary succession

5. Additional negative environmental impacts occur as a result of our ability to undermine ecological succession processes

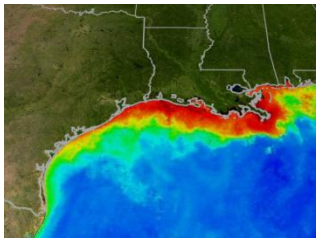
6. Practices that mimic or promote early successional processes will reduce the overall environmental impacts of annual crop production

Agroecosystems conform to the same principles of ecology and laws of physics as do all other ecosystems



Yet, it is apparent that many agroecosystems, particularly annual cropping systems, are managed without explicit consideration of the ecological and physical processes that regulate their functioning!

- Pesticide contamination (Liebman 2001)
- Herbicide resistance (Mortensen et al. 2012)
- Soil erosion (Lal 1990)
- Nitrogen leaching and emissions (Robertson and Vitousek 2009)
- Eutrophication (Cassman et al. 2002)



Given the environmental challenges associated with annual crop production, how might we re-conceptualize annual cropping systems within the context of ecology and physics?

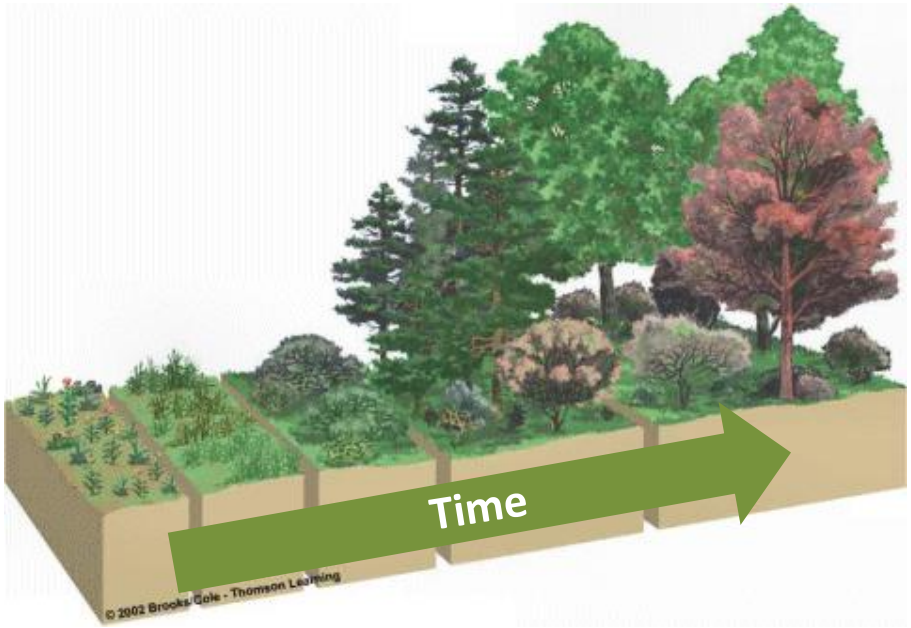
Succession-Energy (S-E) Framework

Potential benefits of viewing agriculture within a S-E Framework

- Large body of data underpinning succession theory
- Theory concerns how plant communities and flows of energy and materials change following disturbance
- Disturbance and conversion of energy and materials to plant and animal products are at the core of agriculture and conform to principles of physics
- S-E Framework provides insight into “why” and “how”

Secondary Succession

- Change in plant community over time following disturbance



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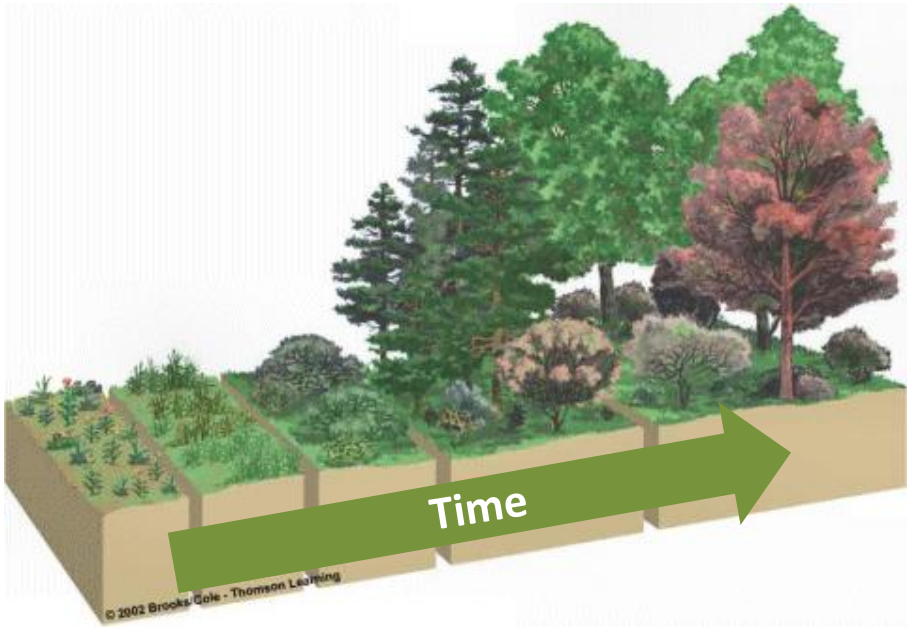

Disturbance

bare soil →

Secondary Succession

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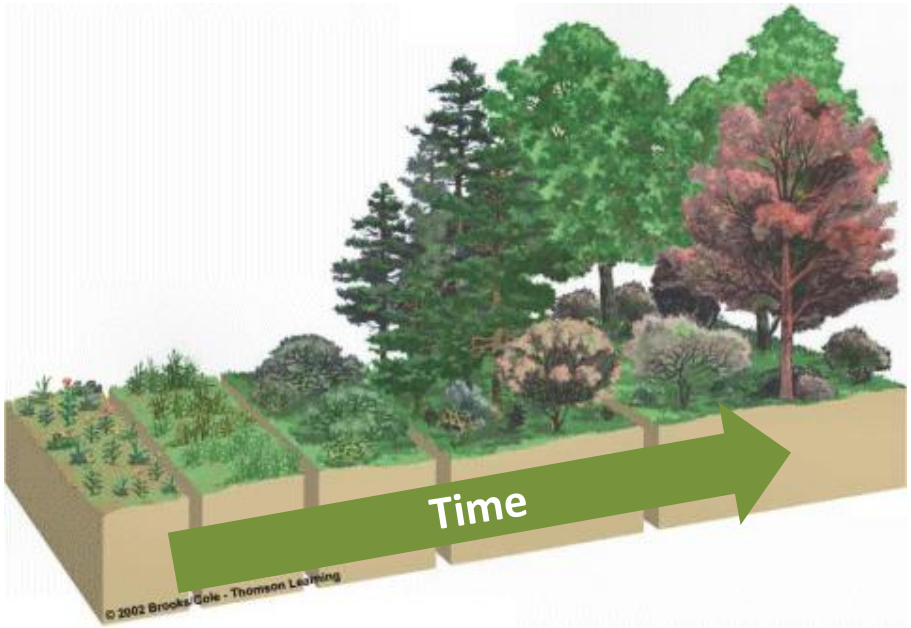

bare soil → herbaceous annuals →

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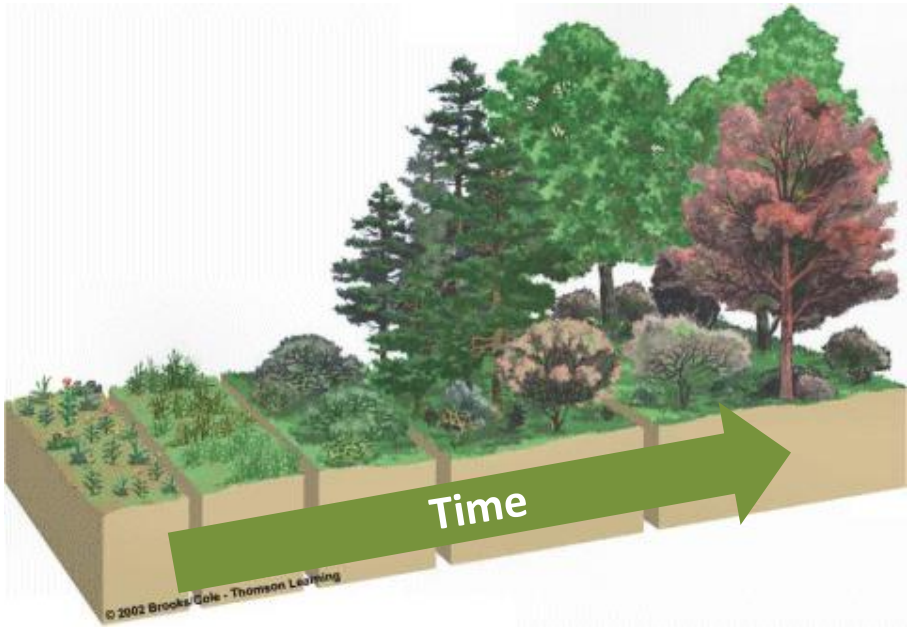

bare soil → herbaceous annuals → herb. perennials→

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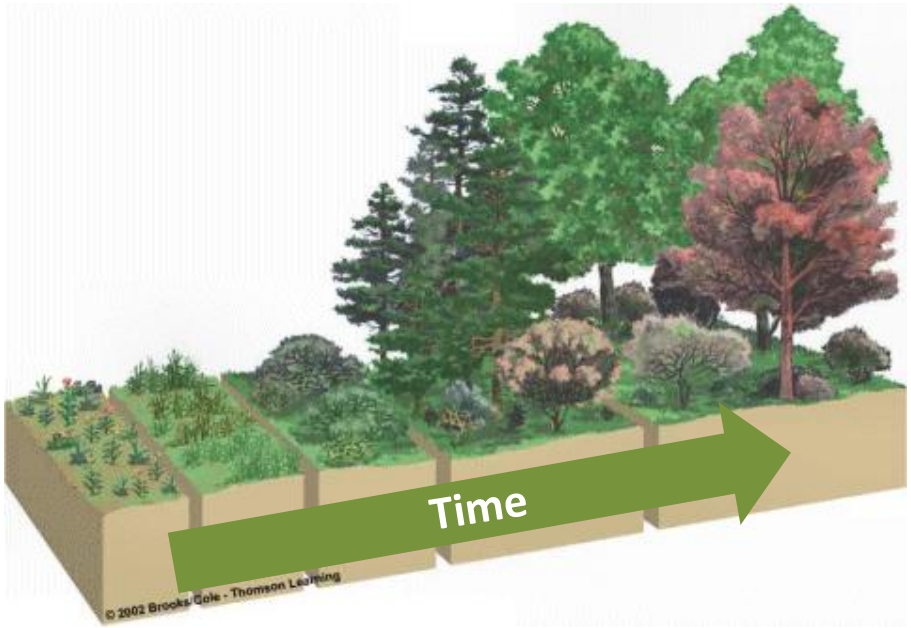

bare soil → herbaceous annuals → herb. perennials→ woody perennials

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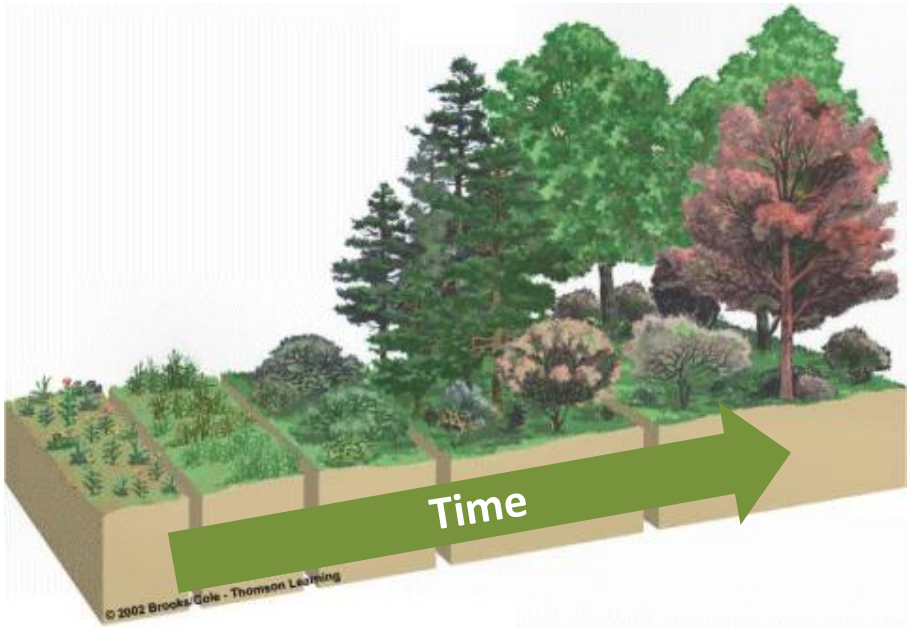

bare soil → herbaceous annuals → herb. perennials → woody perennials

Disturbance

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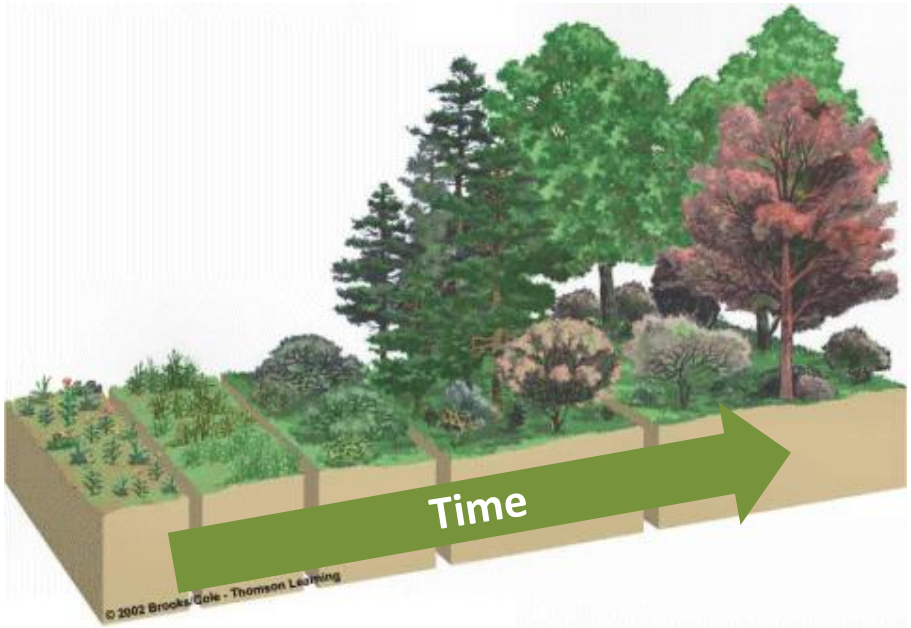


bare soil → herbaceous annuals → herb. perennials → woody perennials

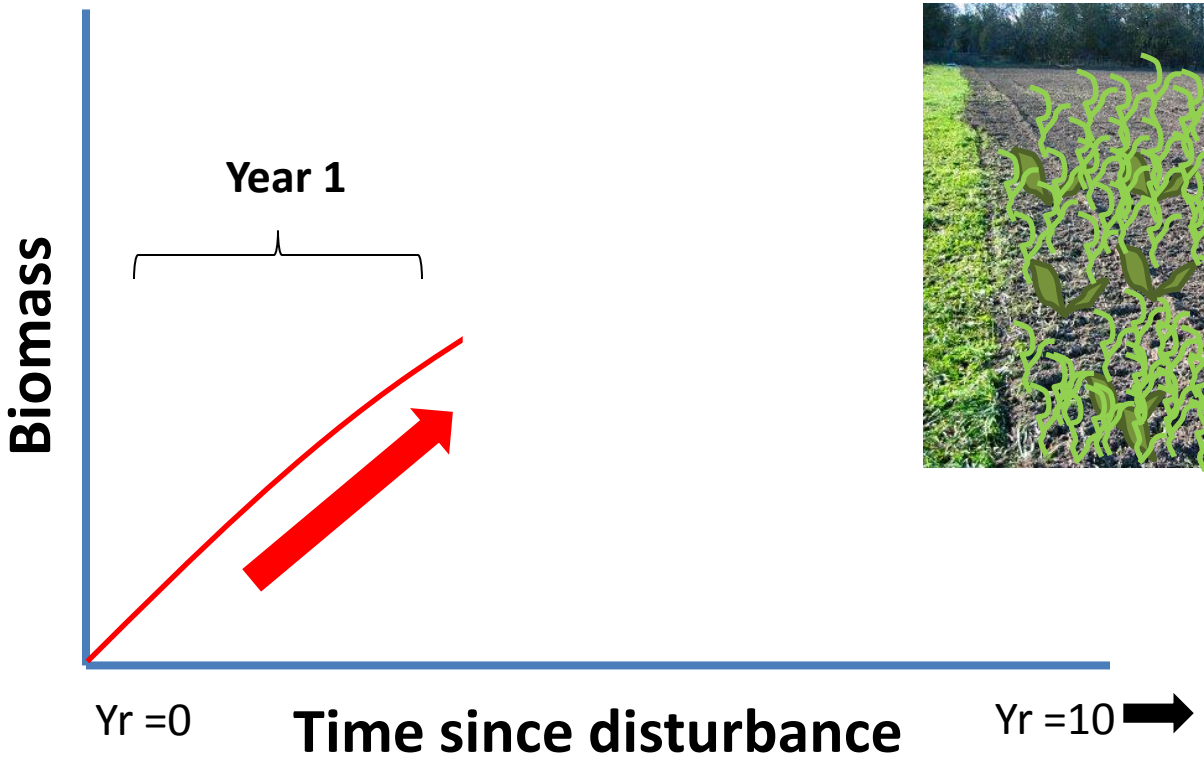
Disturbance

Initiation of secondary succession

- Disturbance initiates succession by creating bare soil

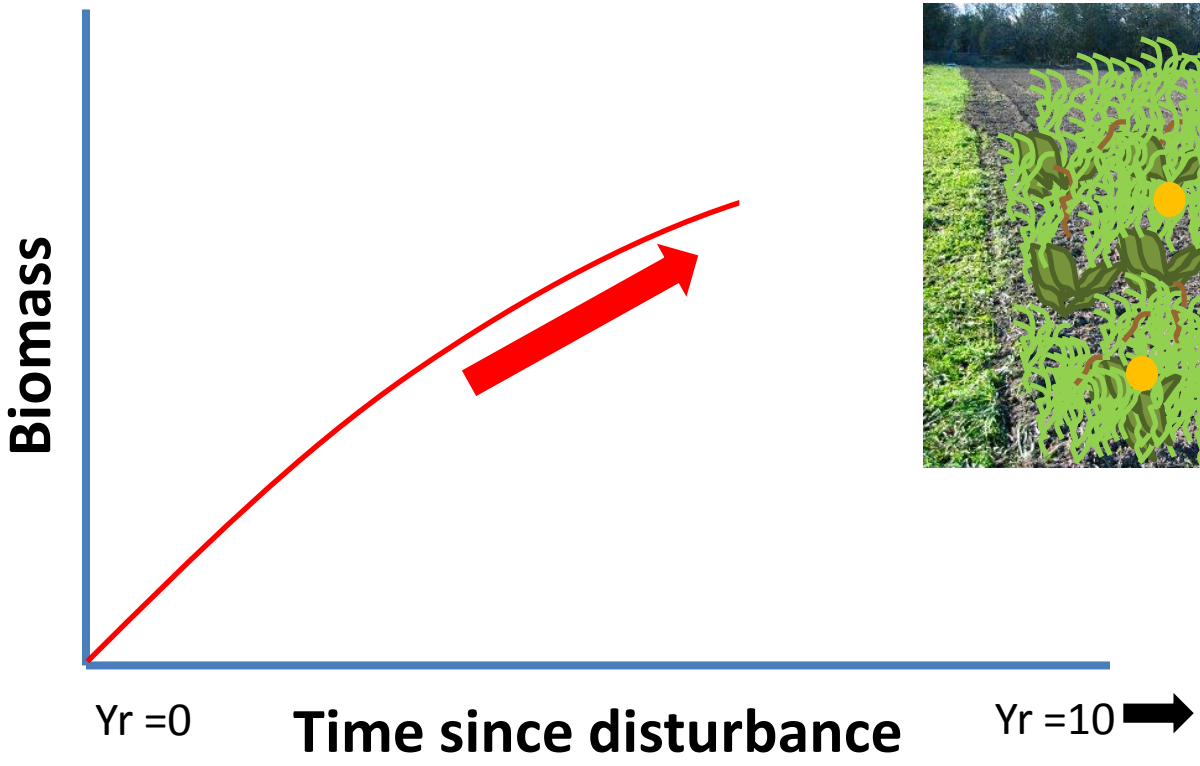
Initiation of secondary succession

- Initially, plant community biomass increases rapidly



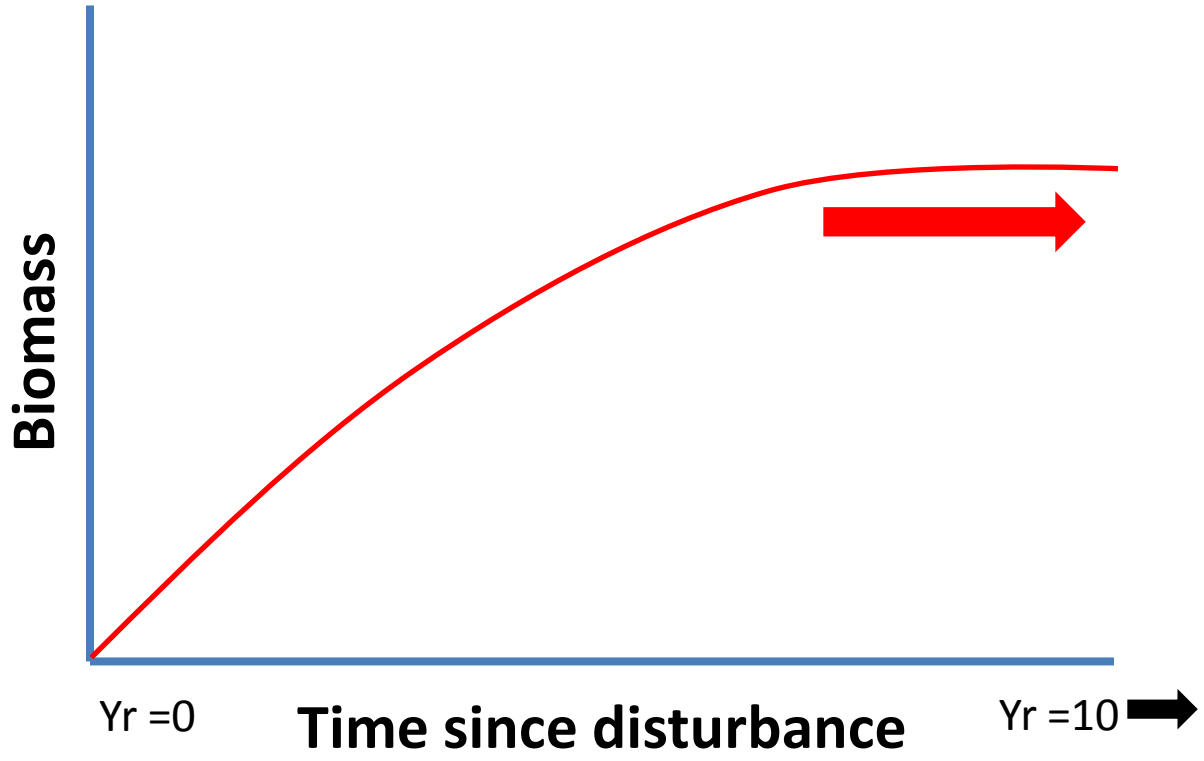
Progression of secondary succession

- Plant community biomass continues to increases with time



Progression of secondary succession

- Accrual of community biomass eventually slows



What else happens during succession?

Metric	Early Succession	Reference
Species richness	↑	Tramer 1975
Biomass allocation to roots	↑	Ewel 1971
Niche complementarity	↑	Odum 1969
Mineral cycles	**open** → **closed**	Odum 1969
Nutrient turnover rates	↓	Vitousek and Reiners 1975

Modified from Hart (1980)

Yes, but how is this relevant to agriculture?

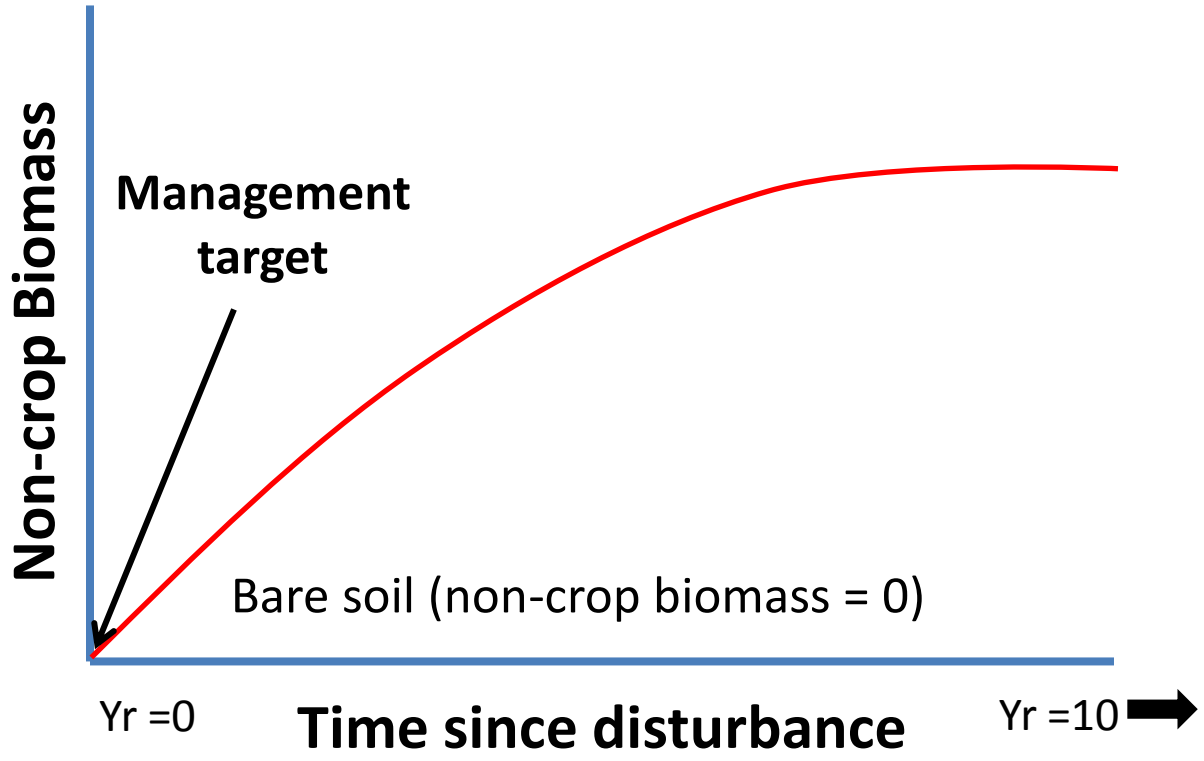
Weeds are succession!

- Weeds are early successional plant species
- Disturbance re-sets succession
- Weeds are the first stage of succession
- So, disturbance results in this….

From Smith (2006) *Weed Science*

But that is not what we want

- Instead, we manage for a perpetual state of initial succession

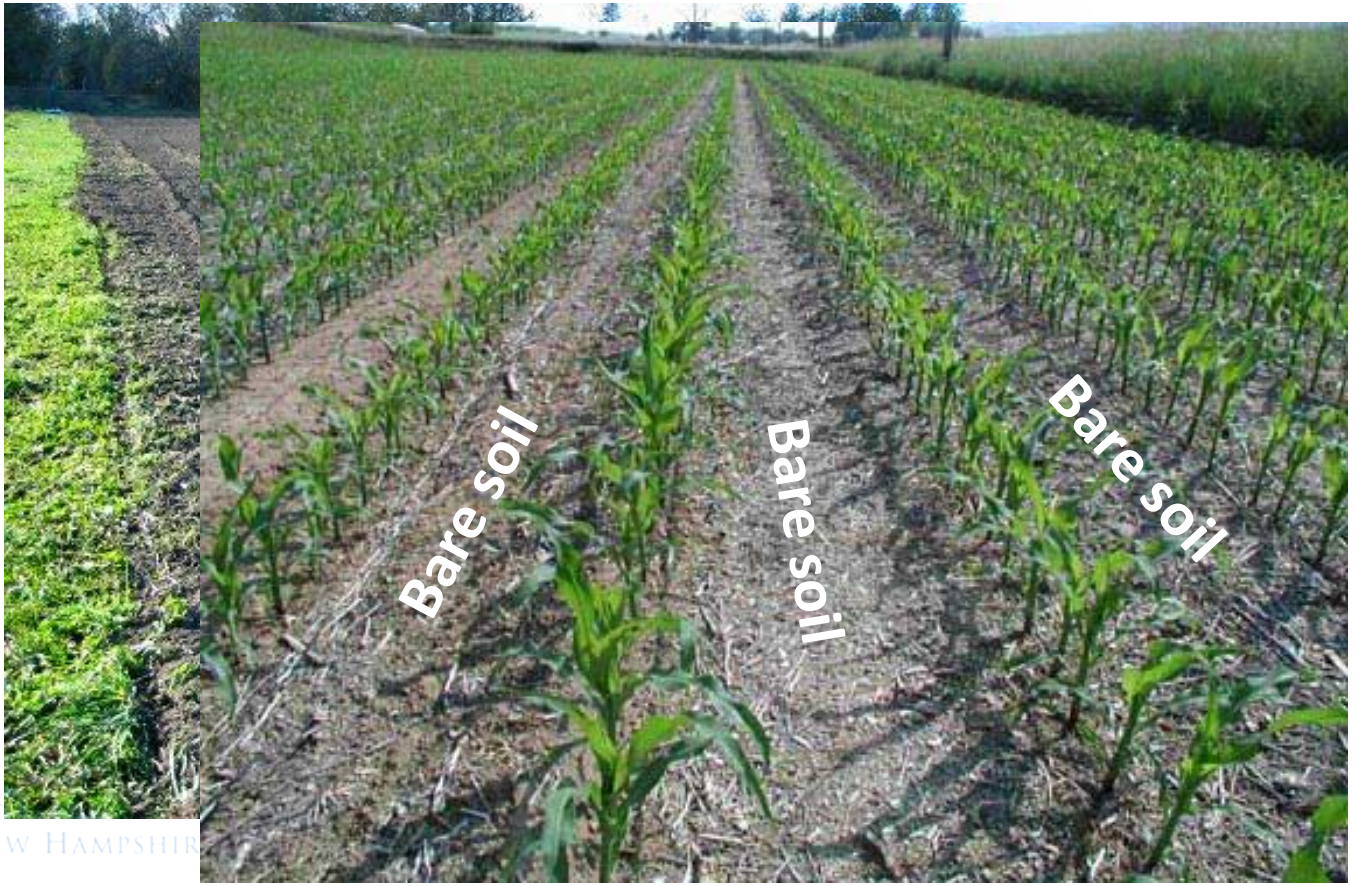


We manage for this

- Perpetual state of initial secondary succession
- **= Bare soil**

We manage for this

- Perpetual state of initial secondary succession
- **= Bare soil**
- **Requires additional disturbance (weed control)…**



We manage for this

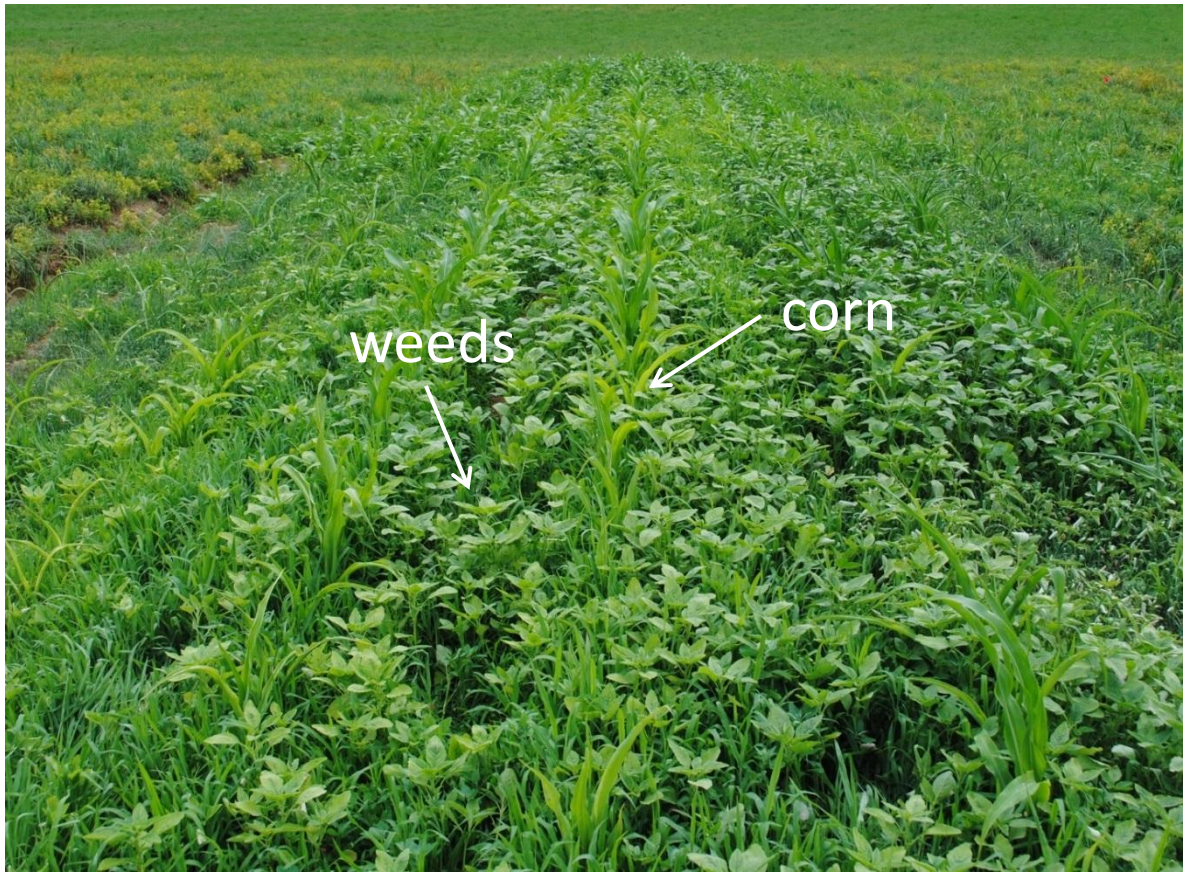
- Perpetual state of initial secondary succession
- **= Bare soil**
- **Requires additional disturbance…every season….**

Otherwise it would look like this

From Smith (2006) *Weed Science*

Or more specifically, this….

- Moldboard plowed, planted corn, no weed control



Or this….

The paradox

- We use disturbance (tillage and/or herbicides) to prepare the soil for planting
- **This disturbance re-initiates succession** (i.e., creates bare soil)
- "Weeds" are the initial stage of succession on this bare soil
- Additional weed management is aimed at maintaining bare soil (except for the crop)
- **This disturbance re-initiates succession**

The paradox

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Our agricultural practices promote weed establishment and growth by continually resetting secondary succession!

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What insight does this provide?

Early successional response

From Smith (2006) *Weed Science*

Early successional response

- The plant community exhibited a successional response to the imposed disturbance

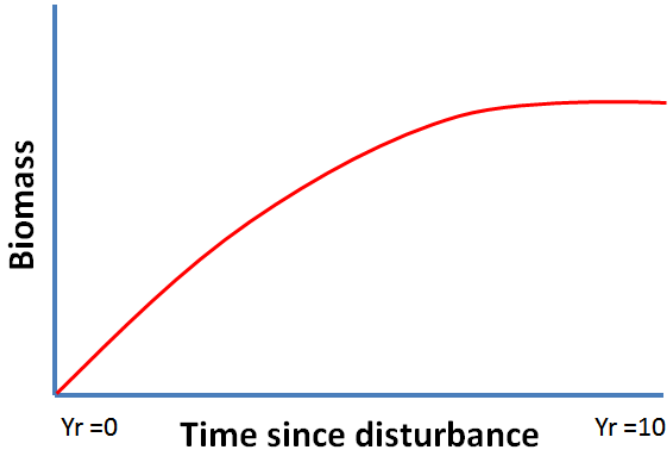
- Disturbance made space, light, and nutrients available (by creating bare soil)

- Early successional plant species (i.e., weeds) responded to these conditions by……..growing

By understanding that weed establishment and growth are fundamentally successional processes, we can derive general principles based on our knowledge of factors that affect the <u>rate of succession</u>

- **Rate of succession (S)** = rate of community biomass accrual (and species turnover)

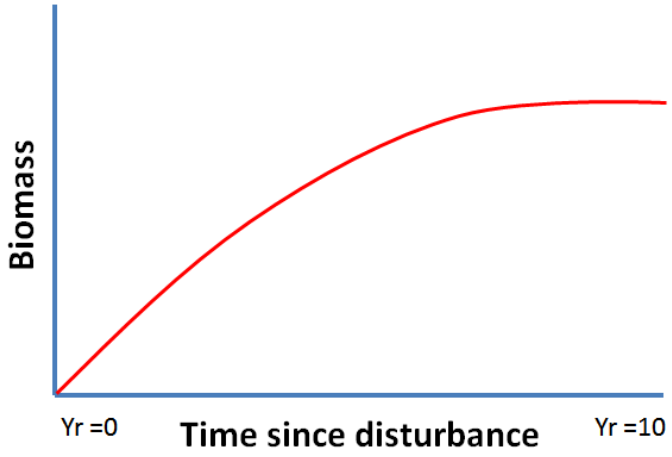
- **Rate of S** = slope of the red line



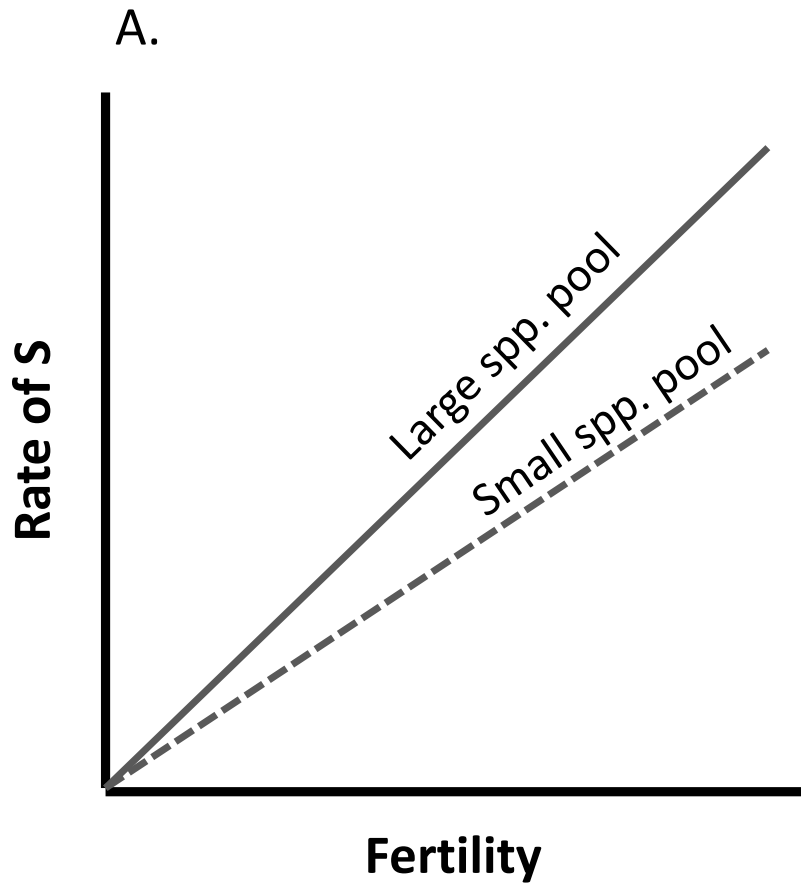
Rate of S is controlled by three factors*:

- **Soil fertility** (site productivity)
- **Species pools** (“weed seed bank”)
- **Successional stage** (time since disturbance)

*Huberty et al. 1998; Huston 1994;
Myster and Pickett 1994; Prach et al. 1993

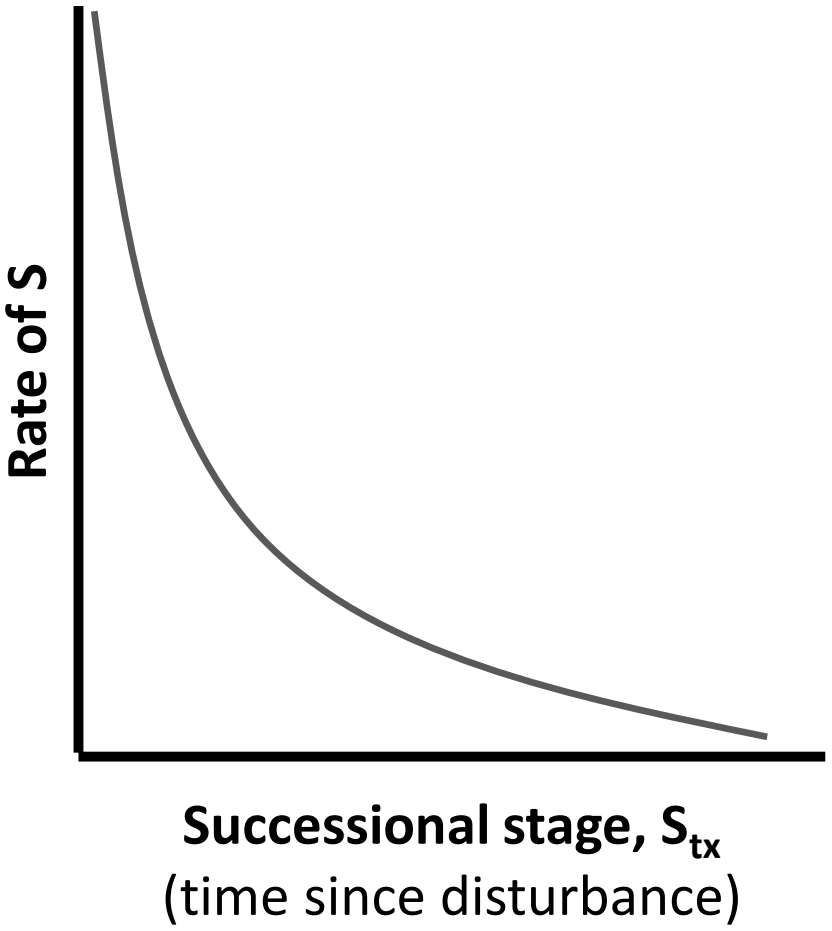


Biomass accrual (rate of S) as a function of soil fertility and species pools



Biomass accrual (rate of S) as a function of time since disturbance

C.



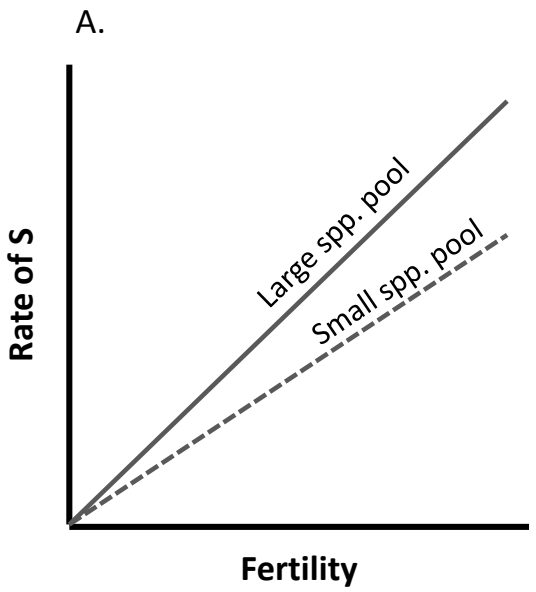
Imagine….

What would have happened if I had added fertilizer after tillage?

From Smith (2006) *Weed Science*

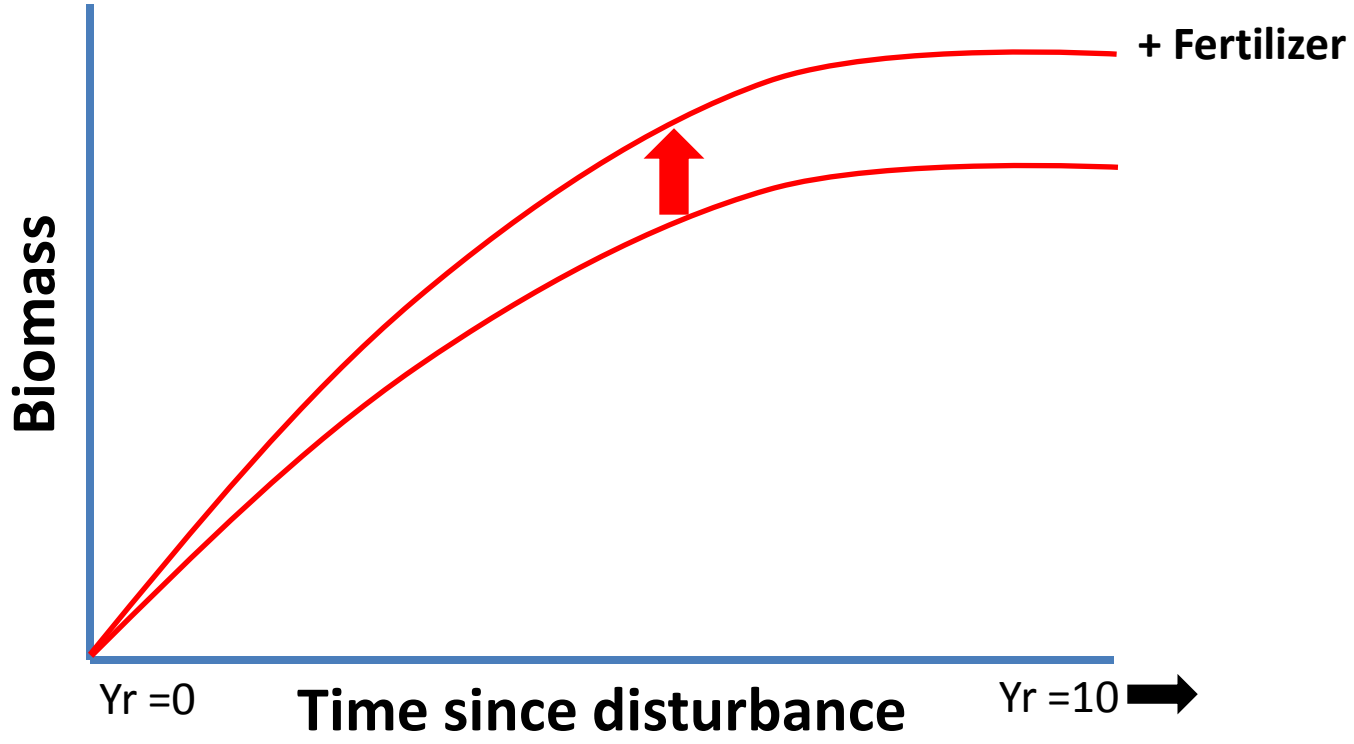
Biomass response to fertilizer

- The plant community would have responded
- Weed community biomass would have increased
- Added nutrients would have been taken up!

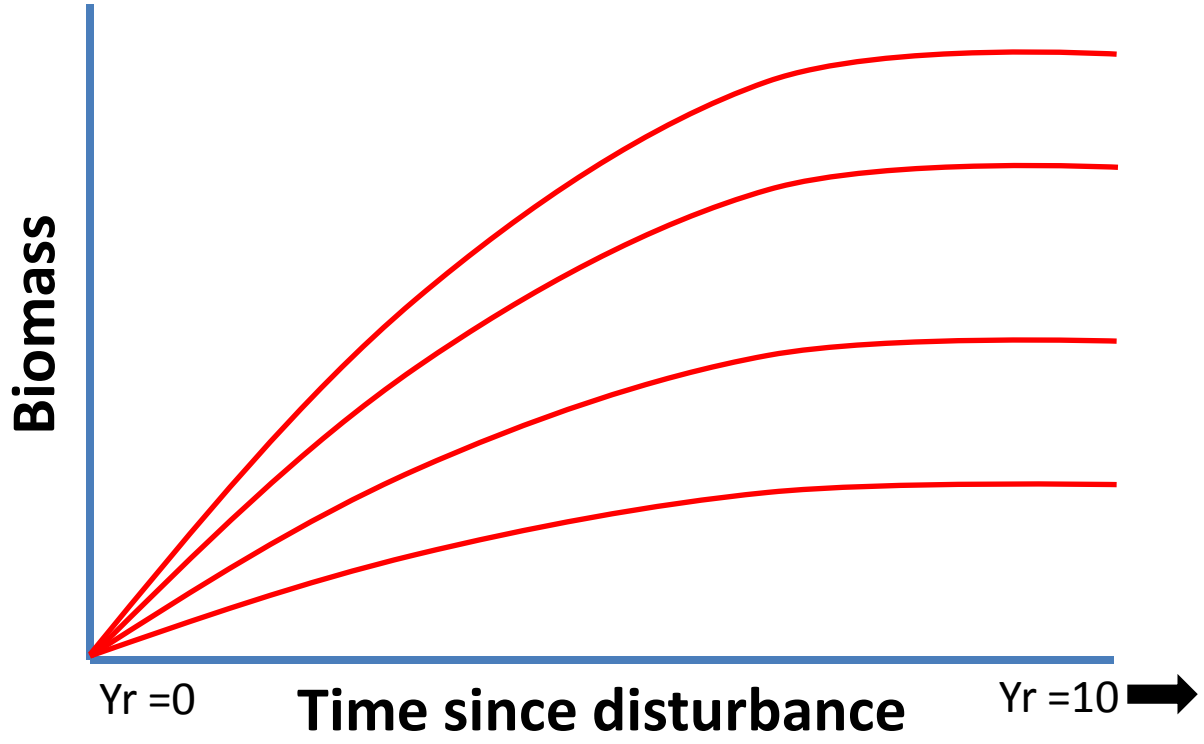


The time-course of succession (late)

Addition of fertilizer increases rate S



Variability in rate of S



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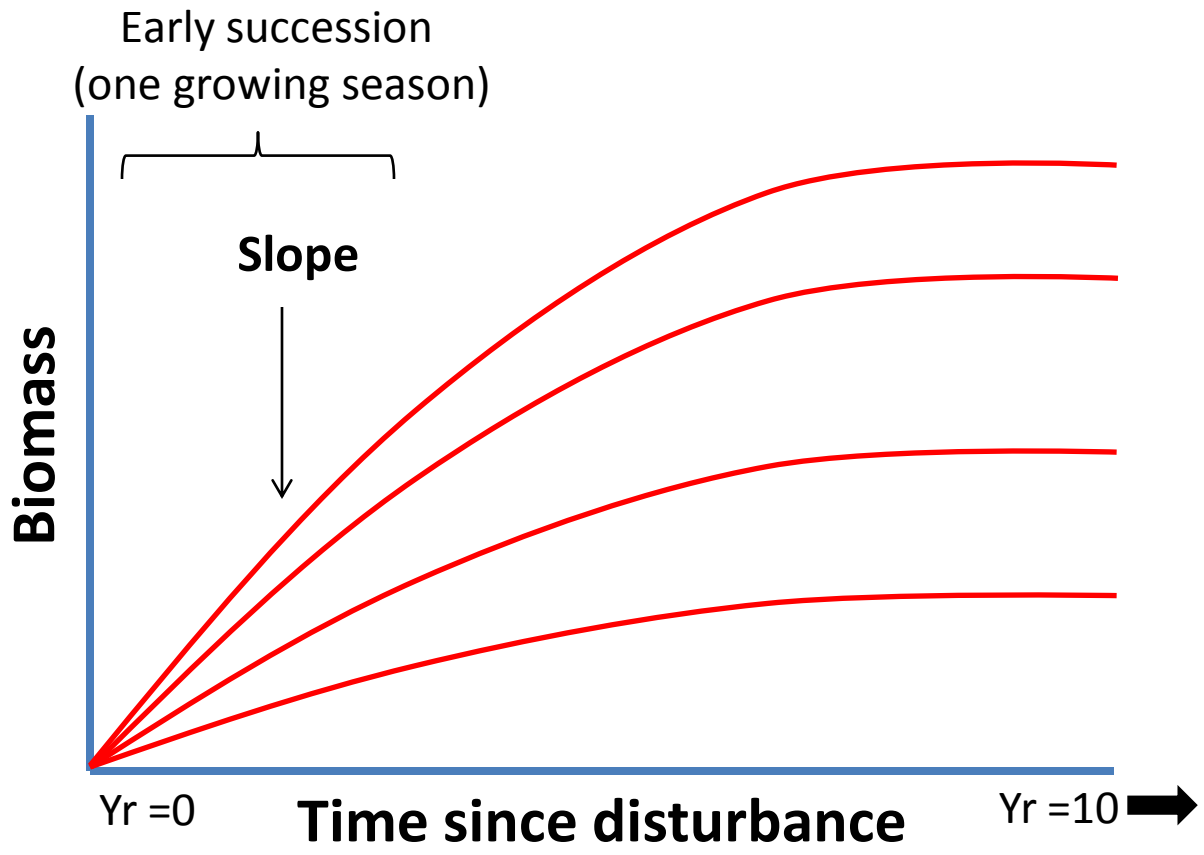

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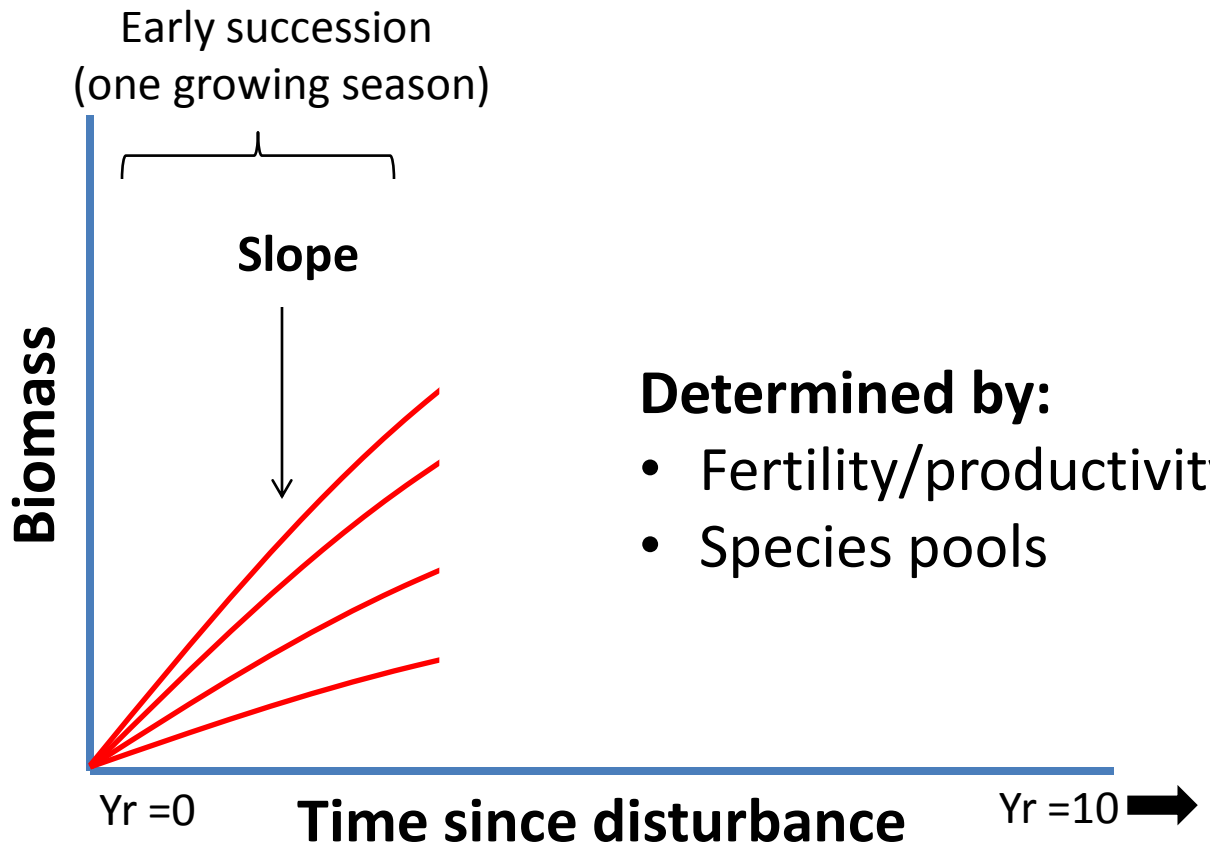
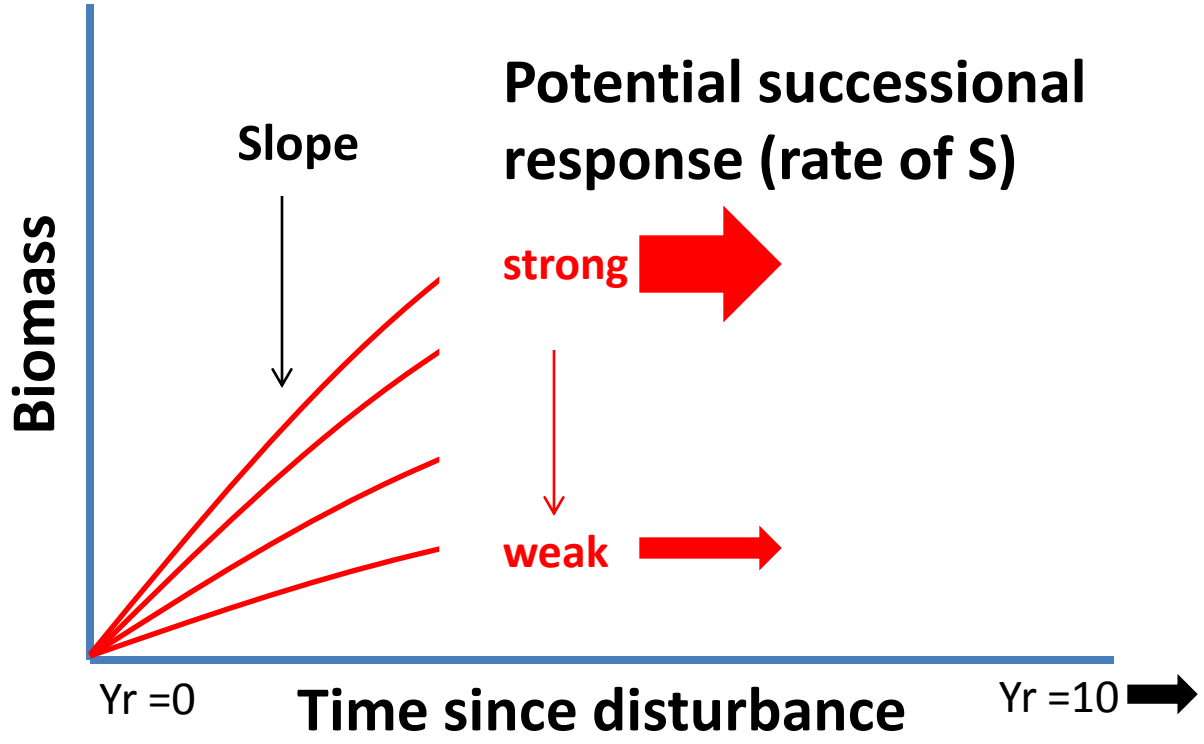


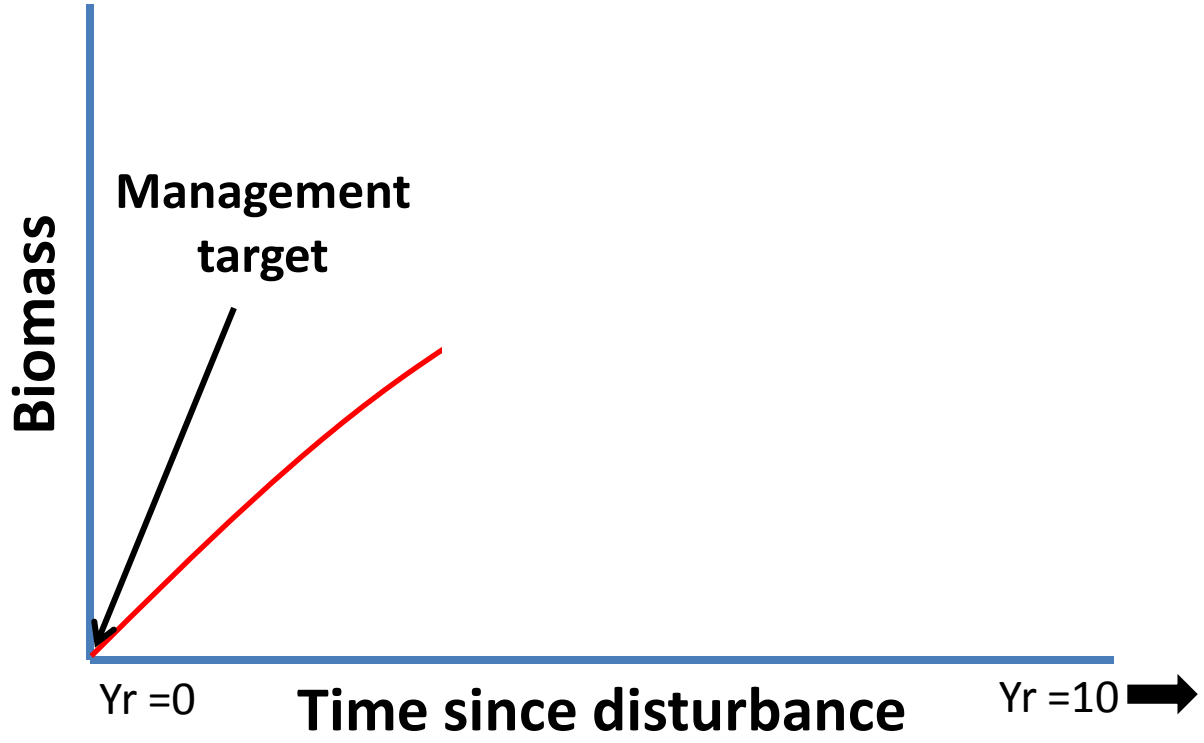
Determined by:

- Fertility/productivity
- Species pools

Variability in rate of S

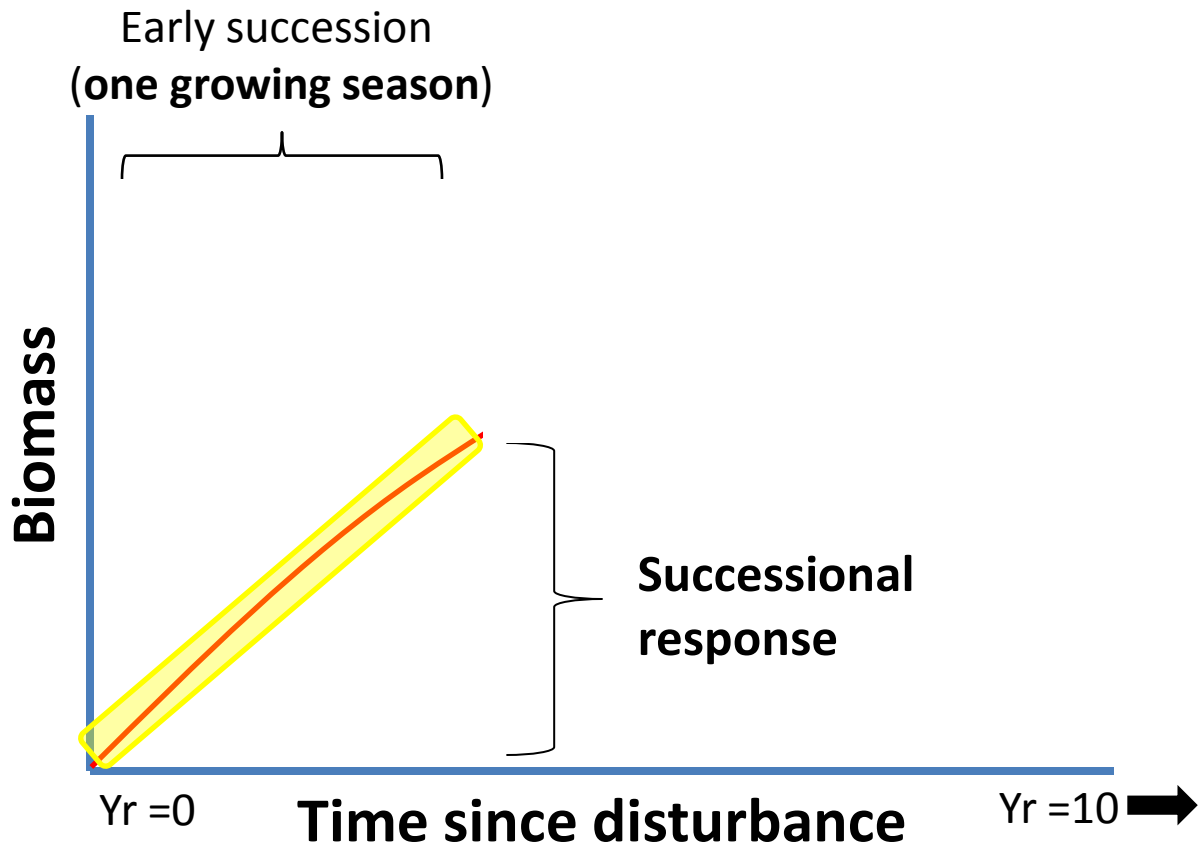


But, the management goal is the initial stage of succession

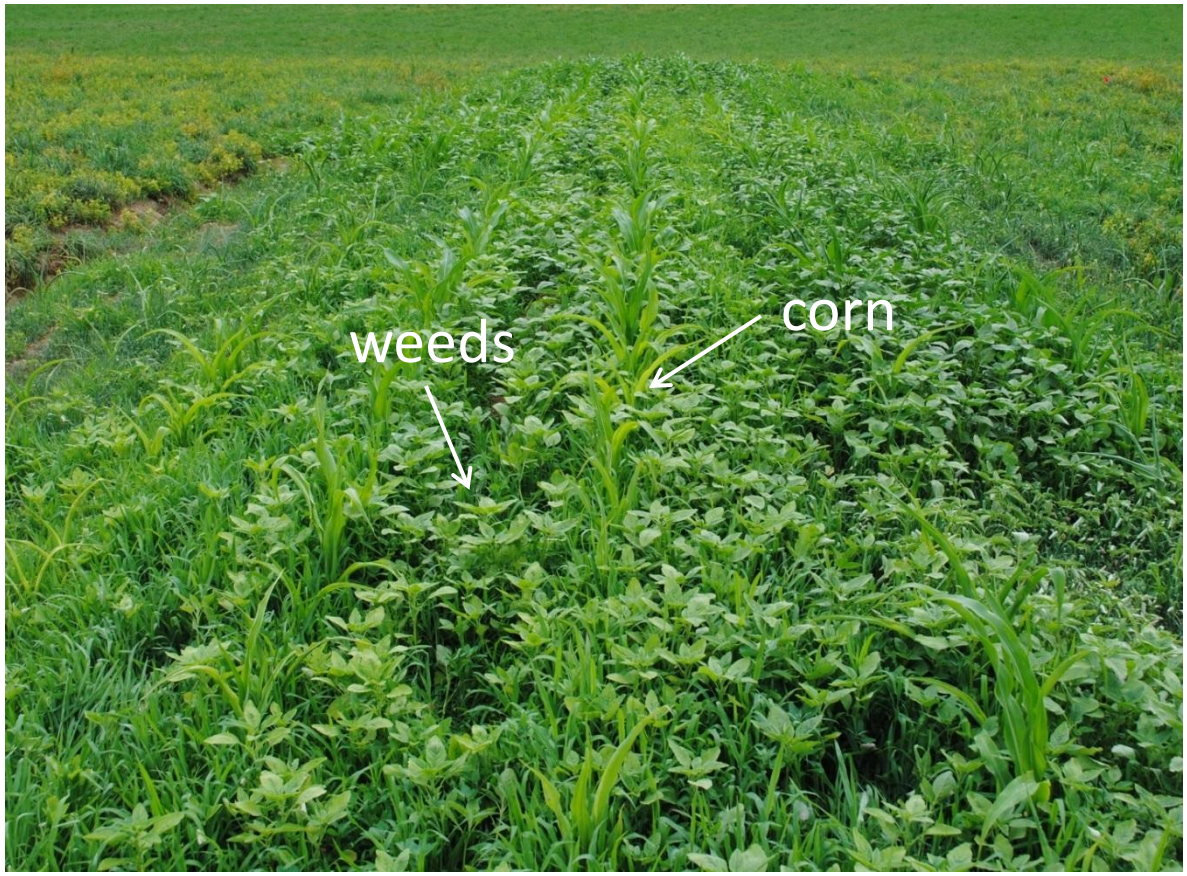


Managing for a perpetual state of **initial secondary succession**

Goal is to suppress successional response

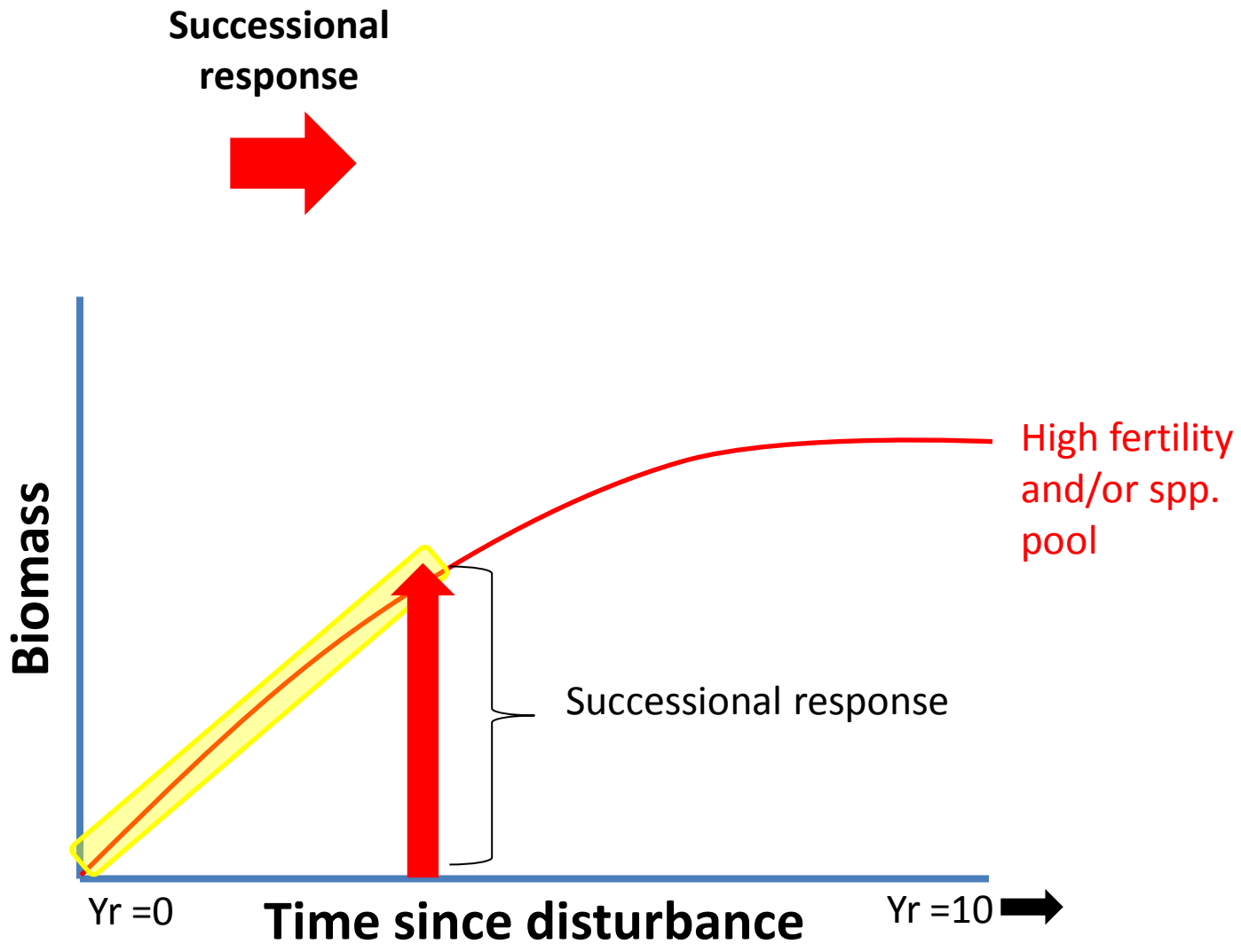


So instead of this…….



We manage for this…….

High rate of succession

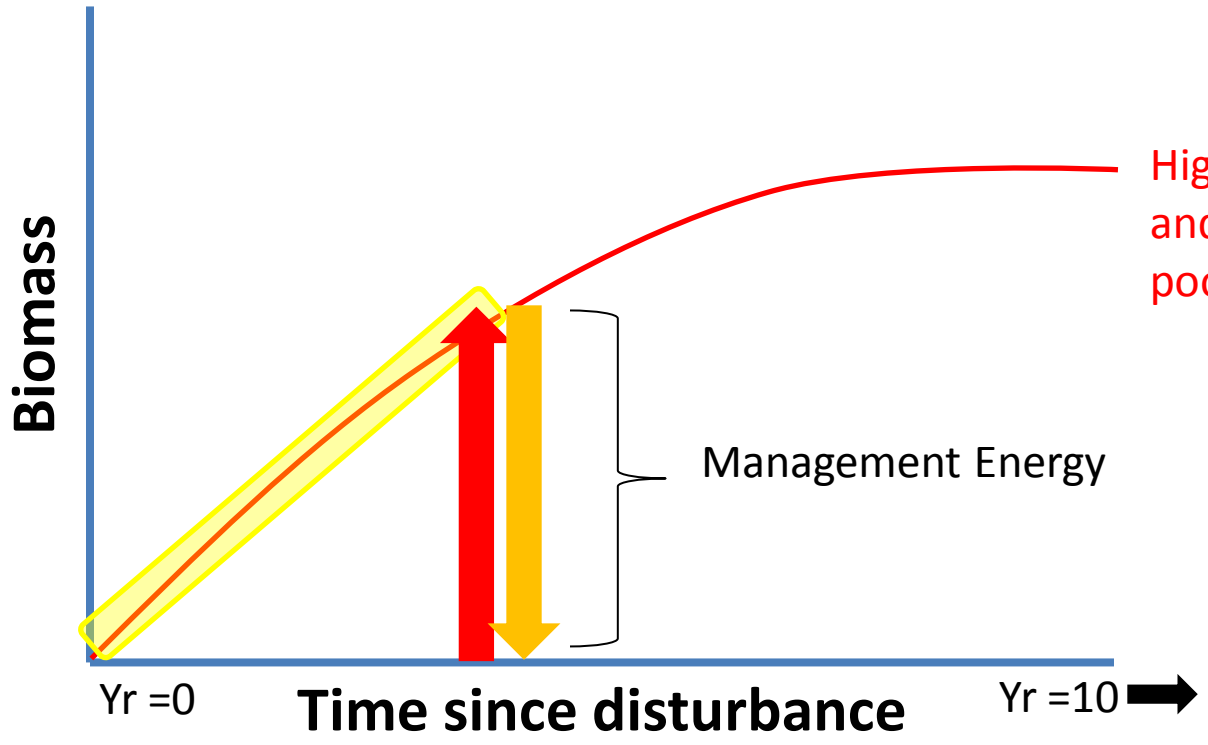


High rate of succession, requires high management energy

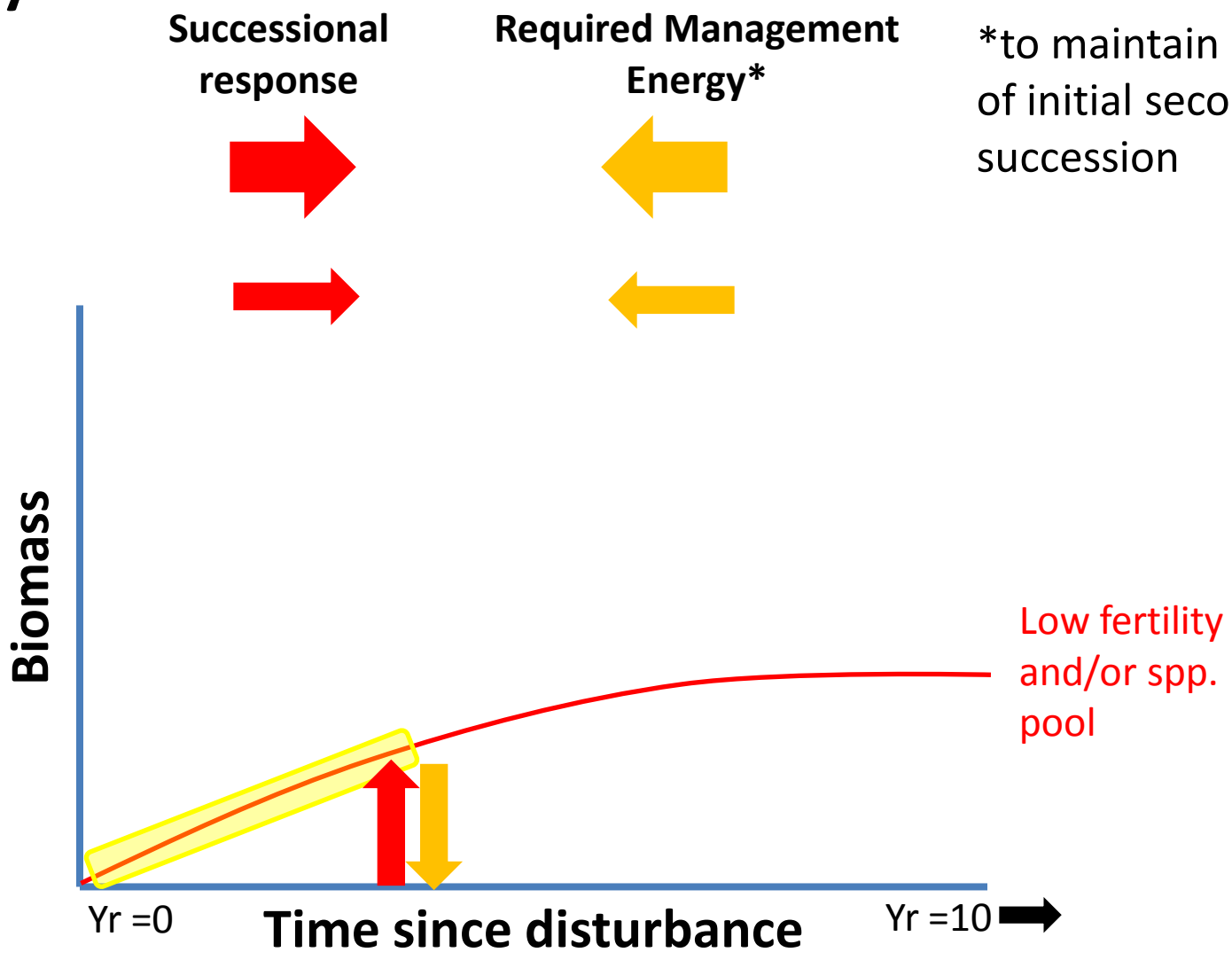
Successional response

Required Management Energy*

*to maintain state of initial secondary succession



Low rate of succession, requires <u>less</u> management energy



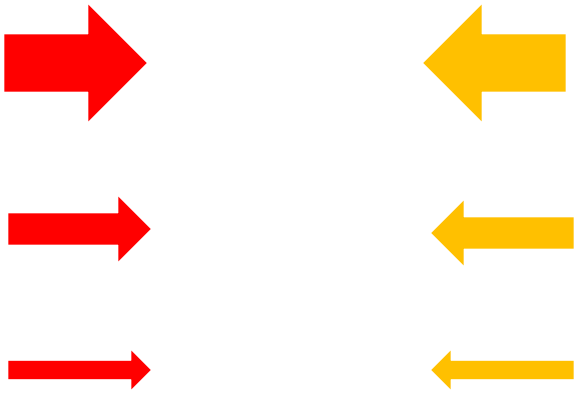
*to maintain state of initial secondary succession

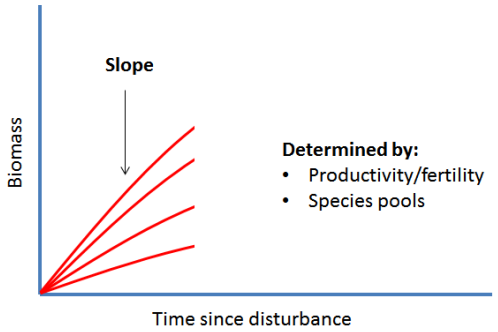
Strength of successional response drives quantity of management energy

Successional response

Required Management Energy*

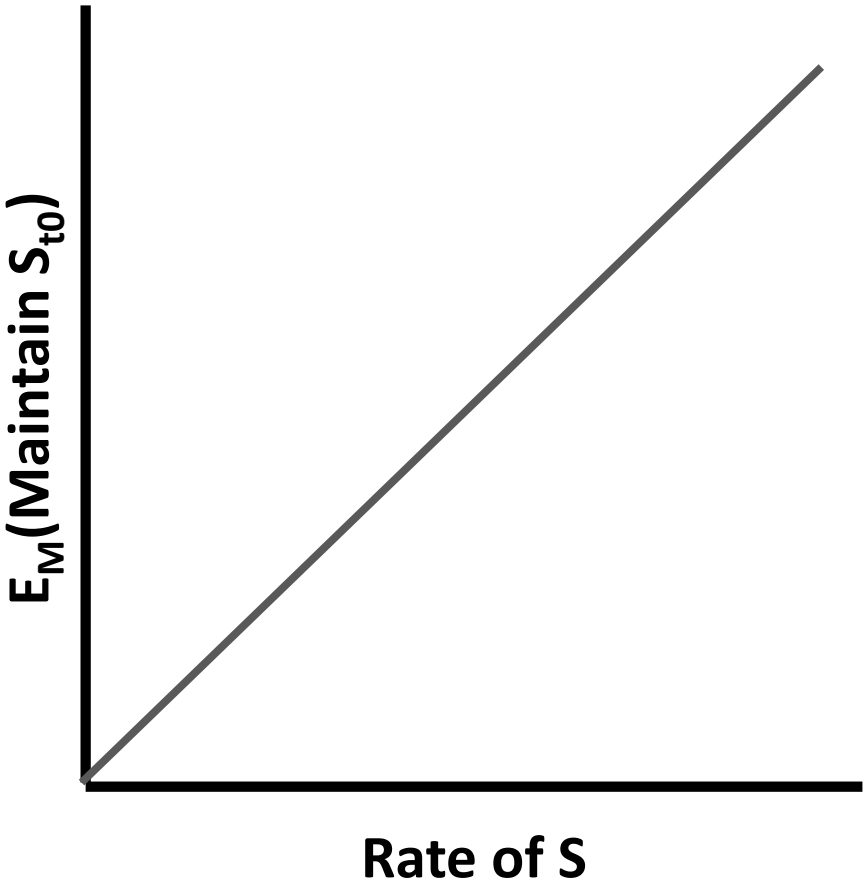
*Tillage
Cultivation
Herbicides



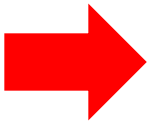
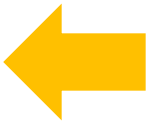


Strength of successional response (rate of S) drives quantity of management energy (E_M)

B.



Quantity of management energy determines scale of environmental impacts

Successional response	Required Management Energy*	Potential for negative impact
		High
		Intermediate
		Low

First Law of Thermodynamics

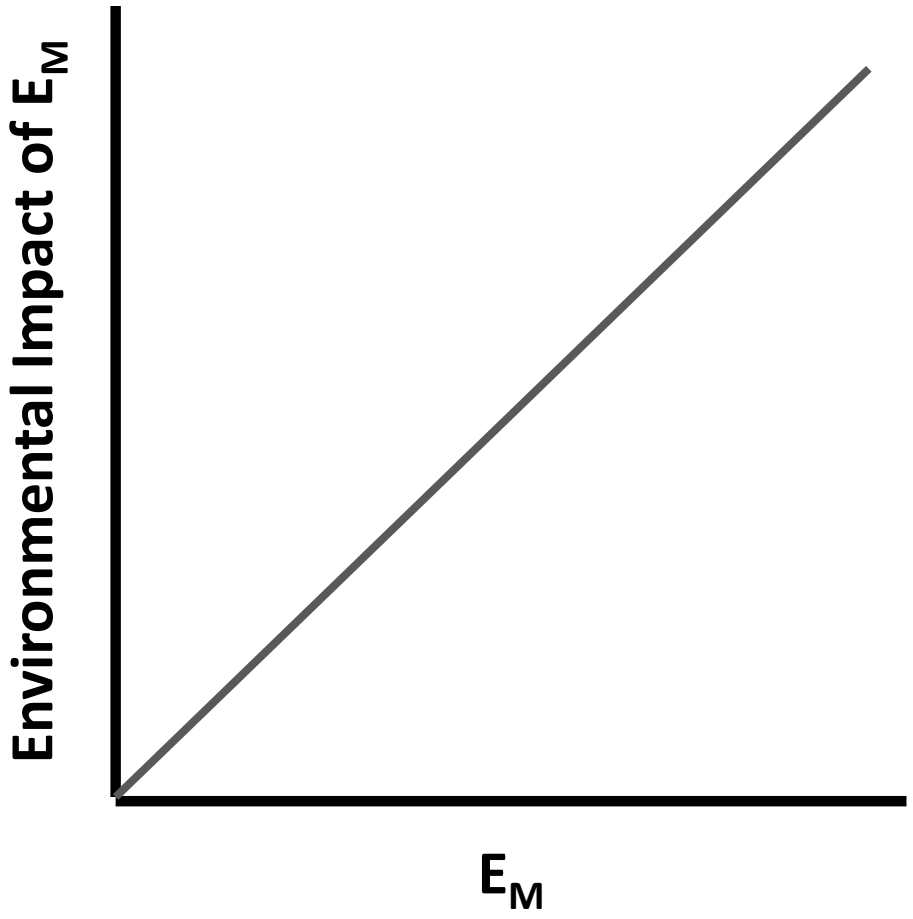
Energy must be

(a) absorbed and converted to other forms of energy, or

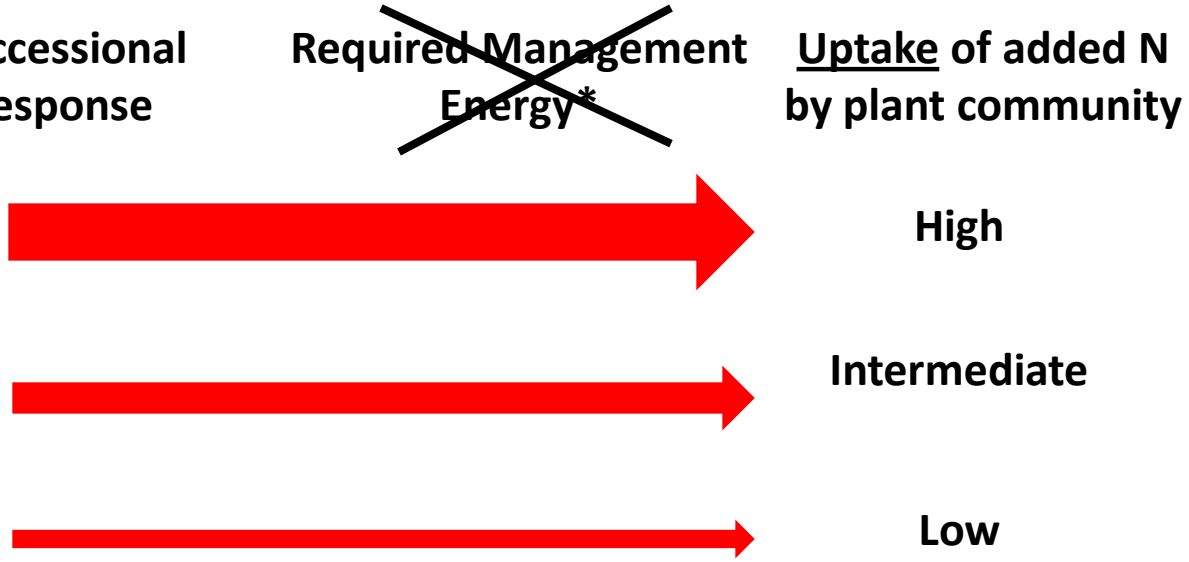
(b) transferred through the system to another system

Quantity of management energy determines scale of environmental impacts

A.



In the absence of management energy…



…….successional plant community (and crop) would absorb additions of nutrients and other perturbations

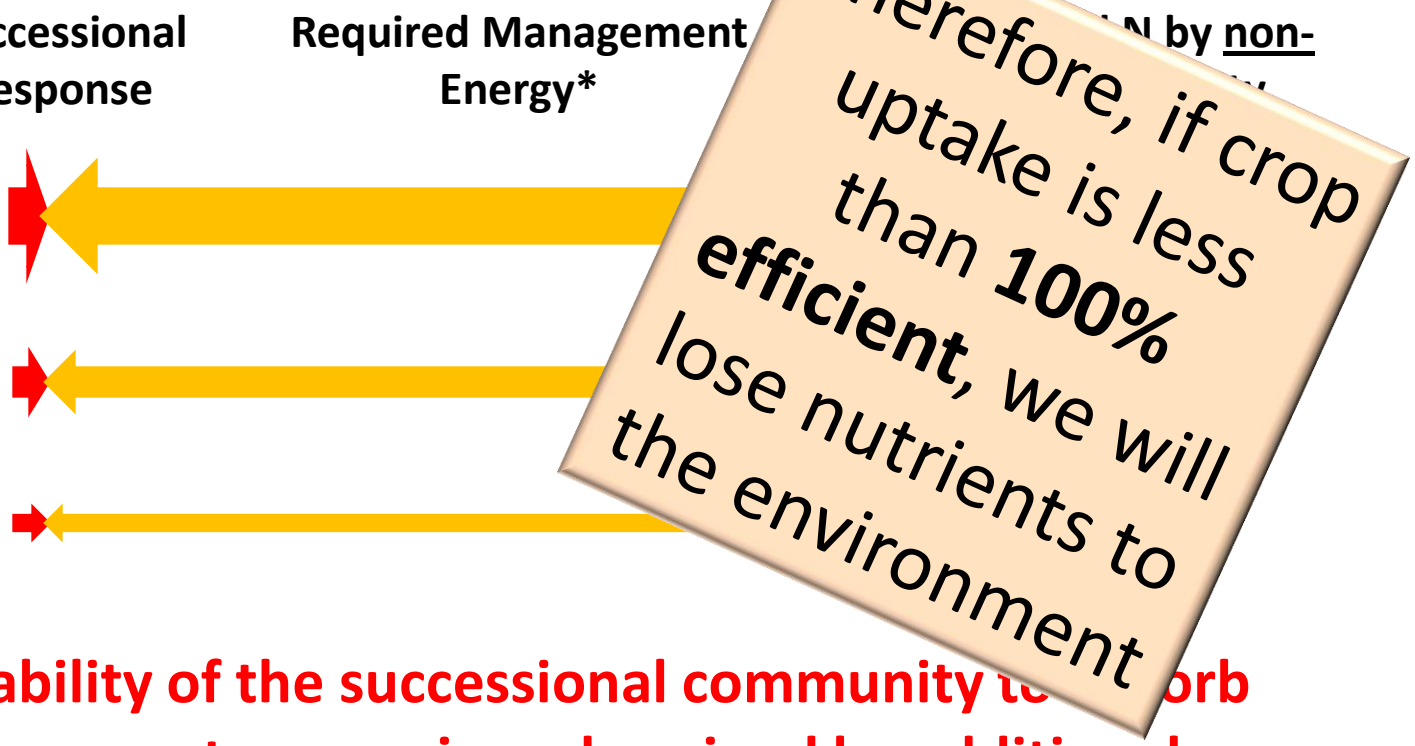
In the absence of management energy…

But, we apply management energy to constrain the successional response

Successional response	Required Management Energy*	Uptake of added N by non-crop plant community
		None
		None
		None

The ability of the successional community to absorb management energy is undermined by additional disturbances and cultivation of mono-specific plant community (i.e. single crop species), etc.

But, we apply management energy to constrain the successional response



The ability of the successional community to absorb management energy is undermined by additional disturbances and cultivation of mono-specific plant community (i.e. single crop species), etc.

Two components of environmental impact from exertion of management energy (E_M)

1. **The management energy necessary to maintain the initial successional state (i.e., to prevent successional processes)**

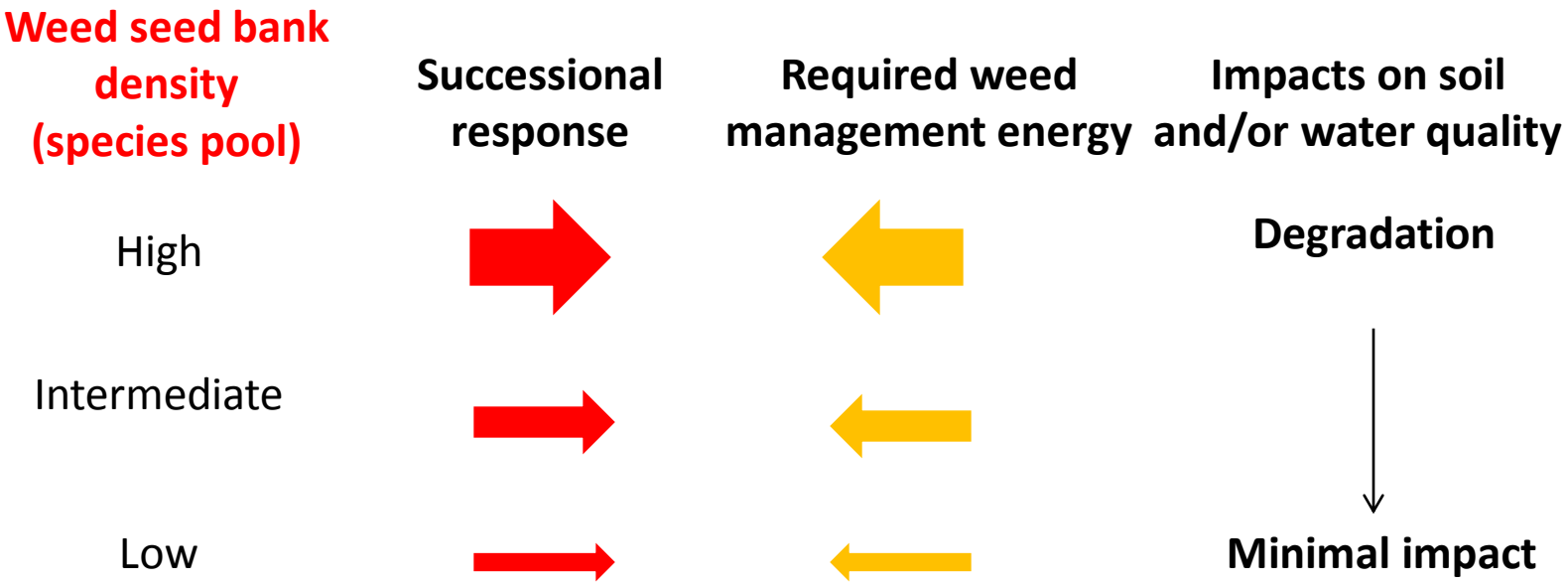
- Tillage/cultivation—soil organic matter, erosion
- Herbicides—water quality, drift

2. **The energy/resources lost from the system due to the suppression of subsequent successional processes**

- Nitrate leaching, trace gas emissions

Because of the relationship between rate of S, management energy, and environmental impact, any change in rate of S will alter the potential for environmental impact

Factors that affect the slope of the successional response (rate of S): species pool



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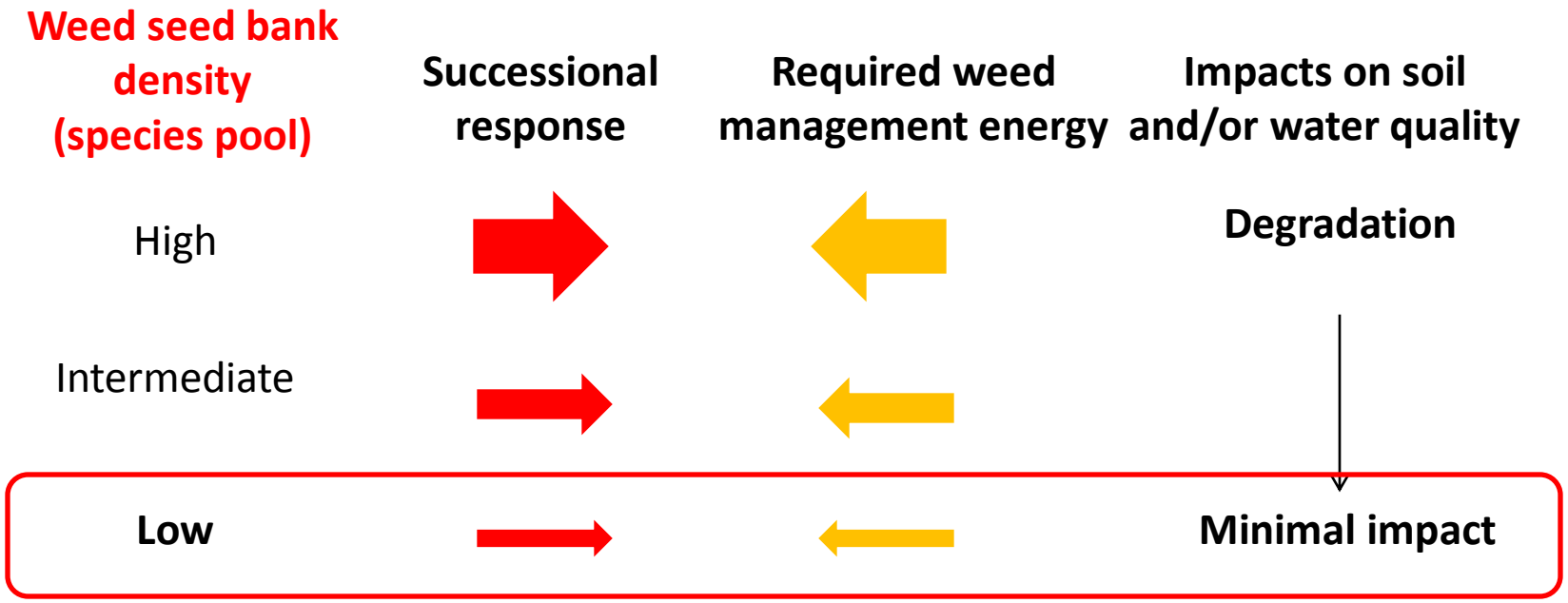
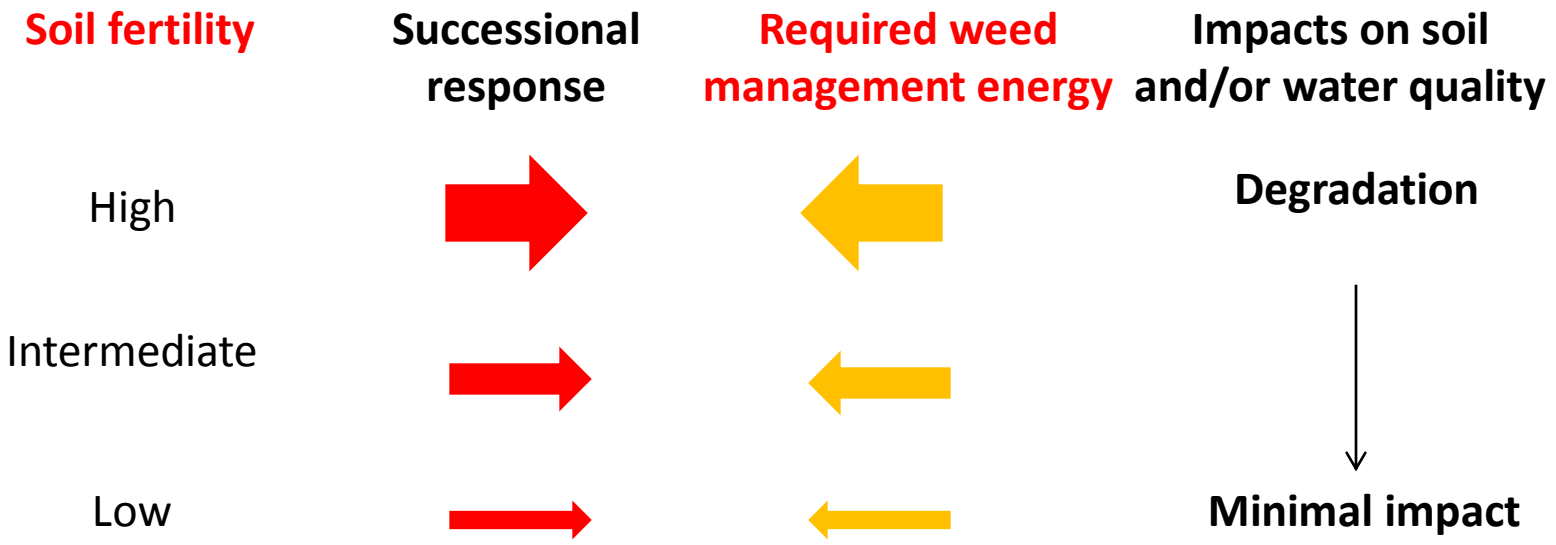


A succession-energy framework provides additional justification for targeting the weed seed bank!

Factors that affect the slope of the successional response (rate of S): Soil fertility



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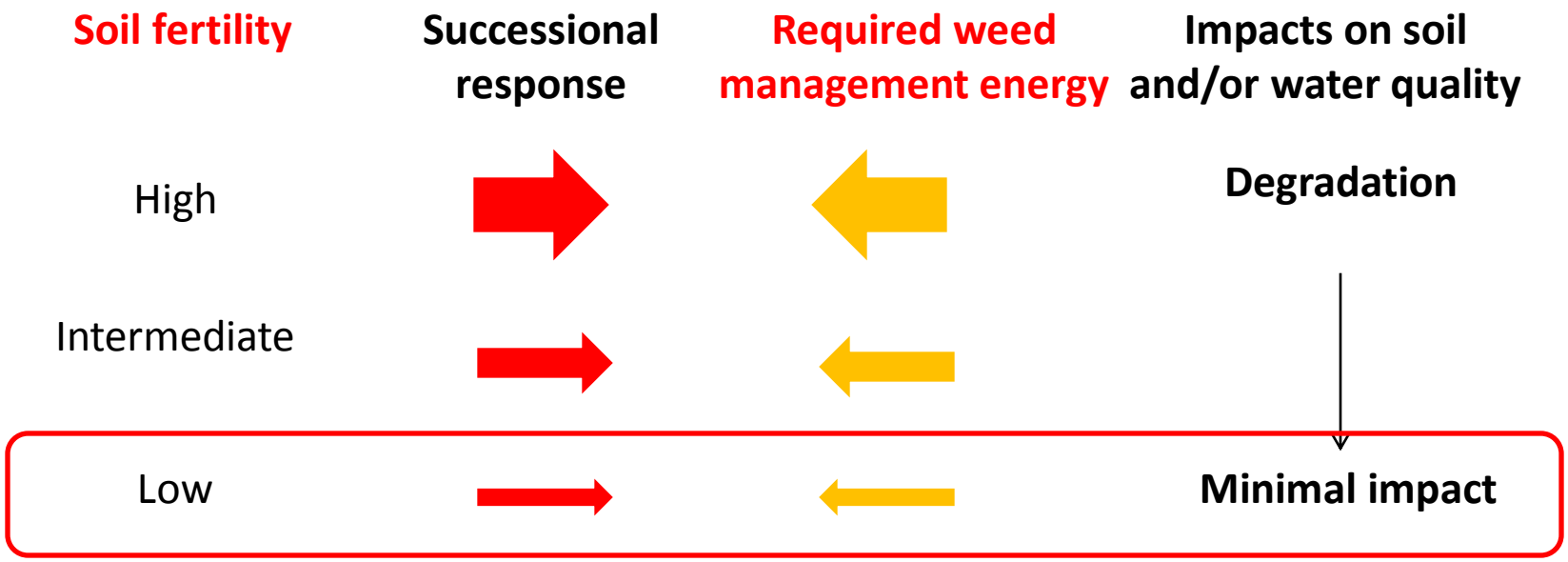
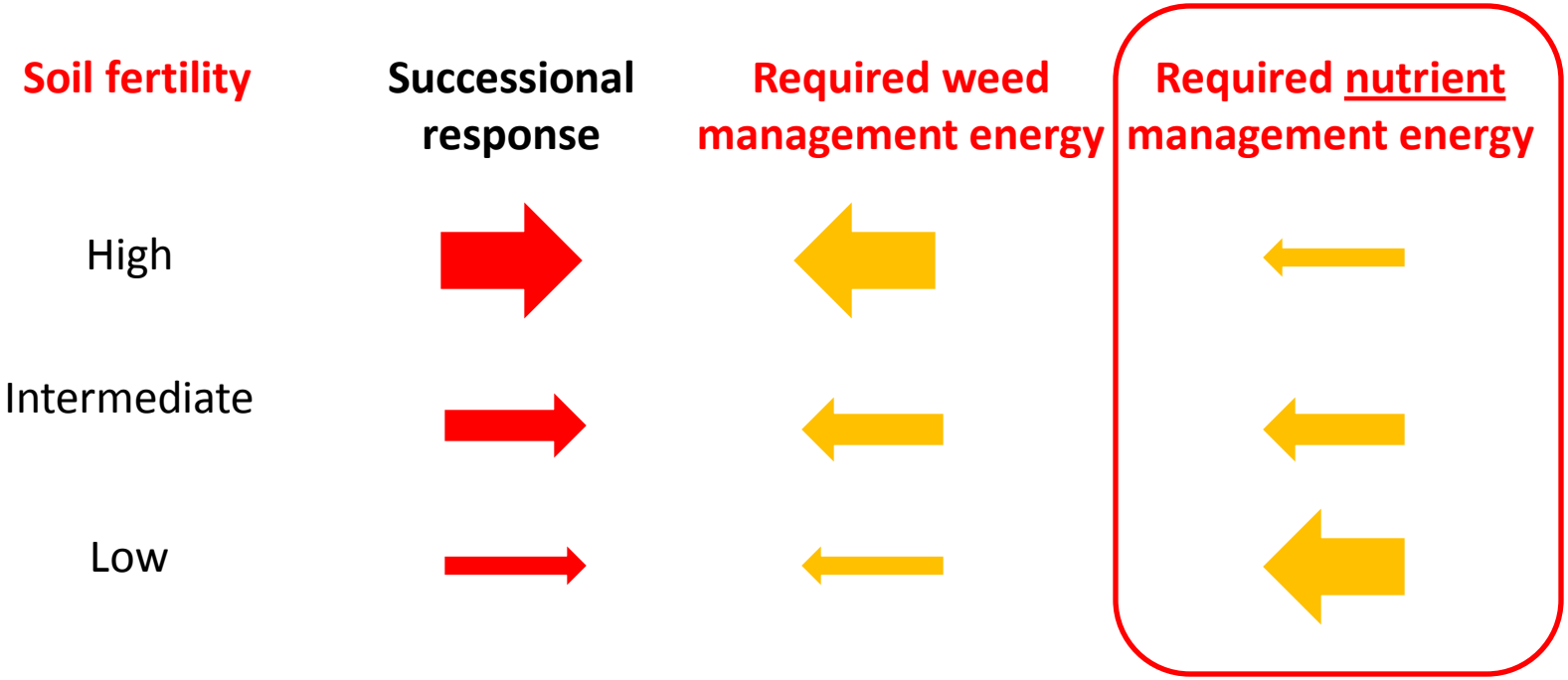


Low soil fertility sites would require low expenditure of weed management energy

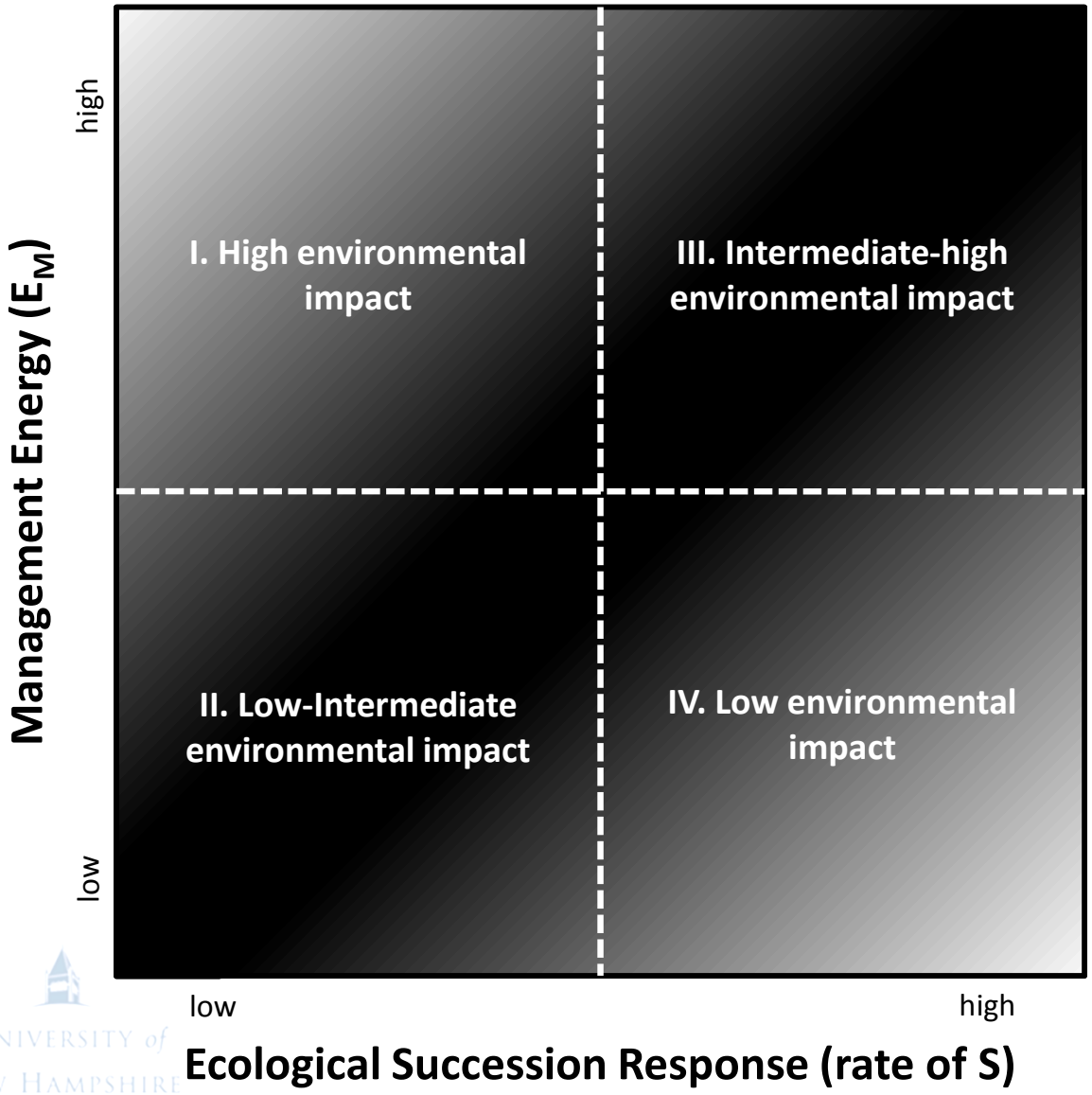
Factors that affect the slope of the successional response (rate of S): Soil fertility



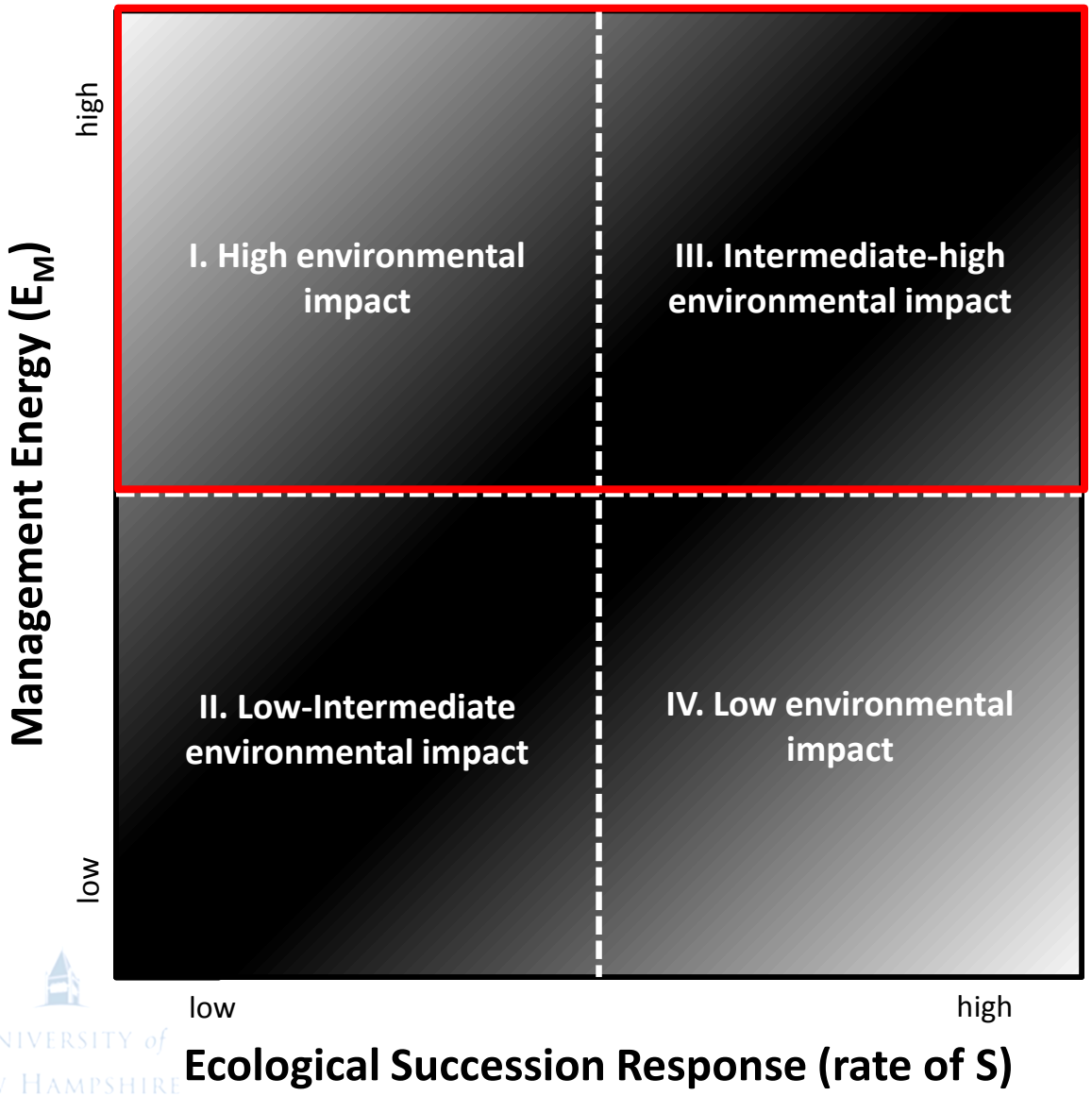
Crop yield goals may necessitate other types of management energy!!! What are the trade-offs?

Putting it all together

Dynamic interplay between rate of S, E_M, and environmental impact



Putting it all together



Our conventional cropping systems tend to operate in these zones

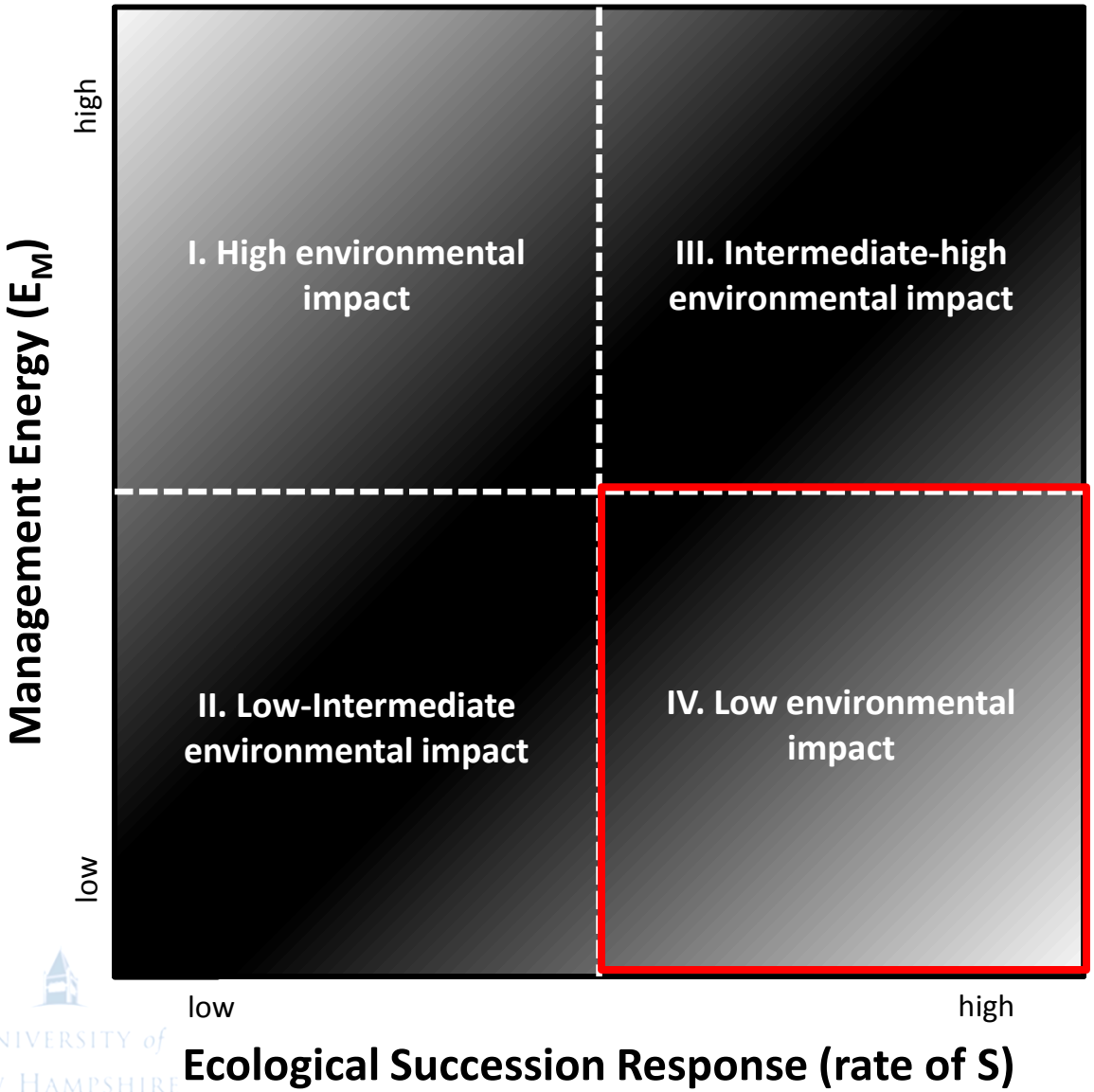
Zone III: High energy expenditures aimed at suppressing successional response

- High weed pressure

Zone I: High energy to increase fertility and/or productivity

- Exceeds capacity of crop community (weeds and crop) to "absorb" inputs
- Ex: low productivity environments

Putting it all together



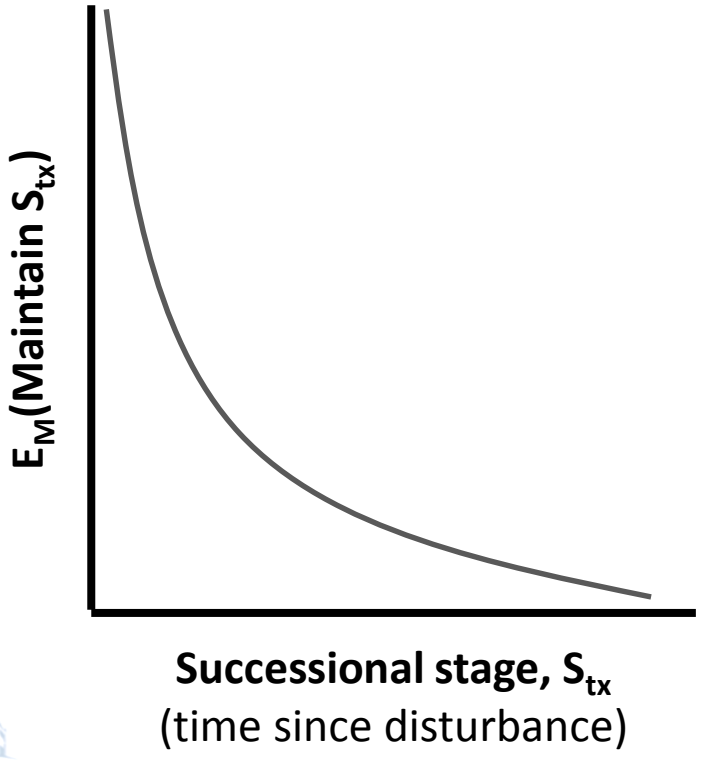
Ideally, we would be operating in zone IV

High fertility/productivity, but requiring minimal management energy

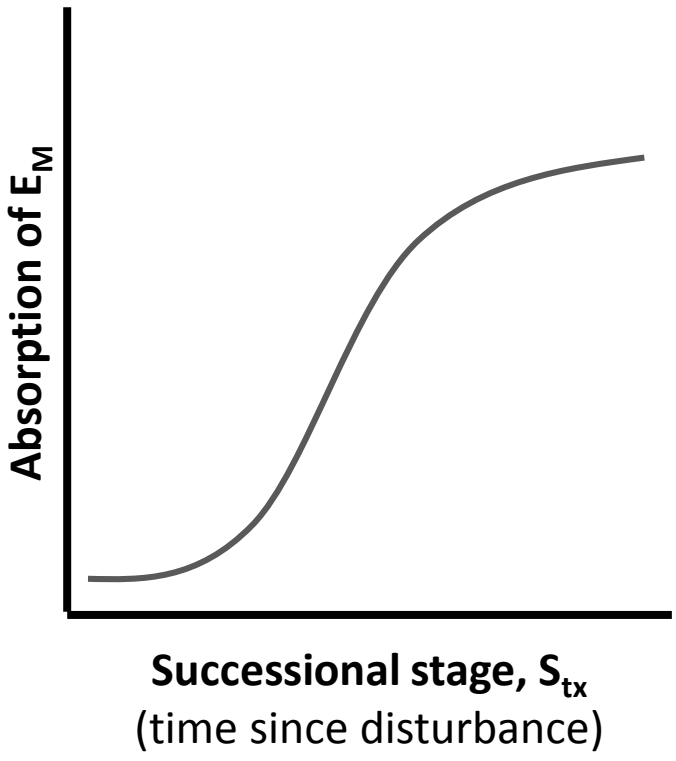
- How do we get there?

Goal should be to <u>replicate</u> later successional communities <u>within</u> our annual crop systems, as these require less energy to maintain and more readily absorb any additional energy inputs

A.



C.



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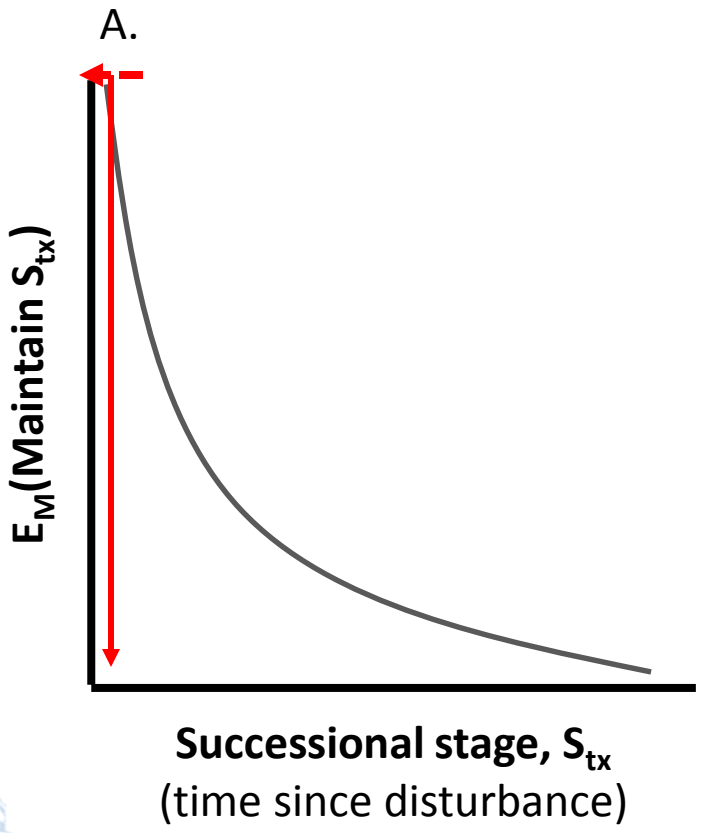

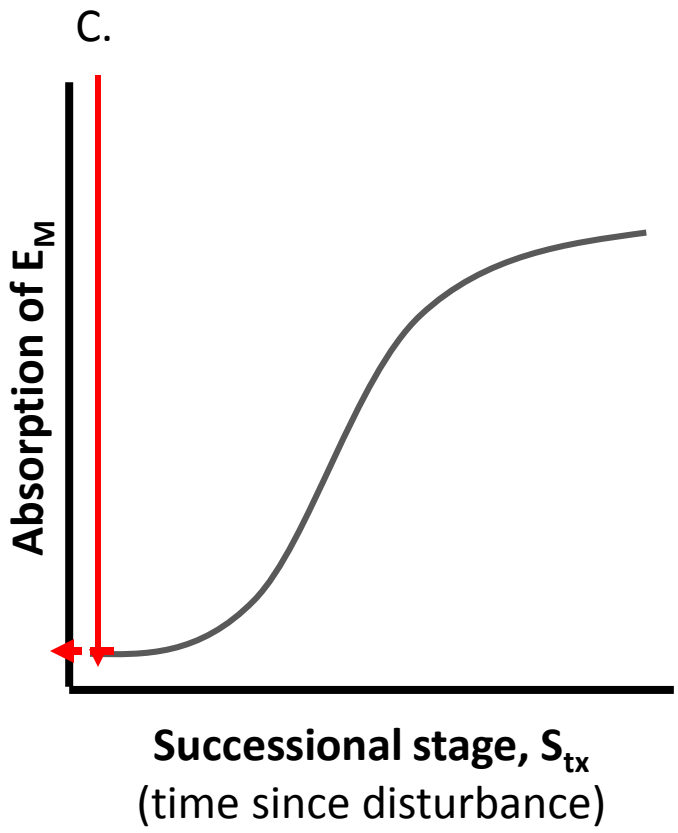

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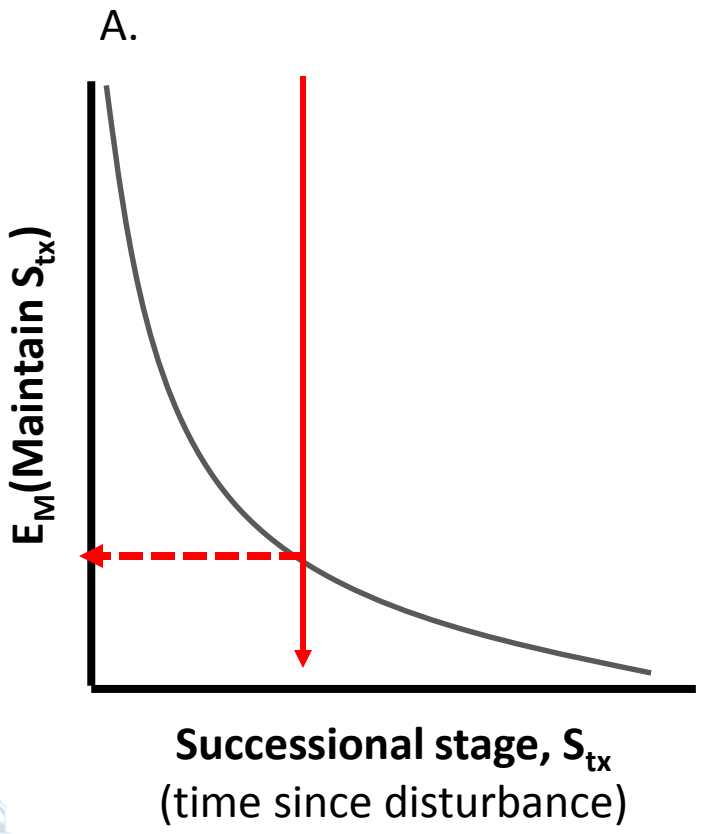

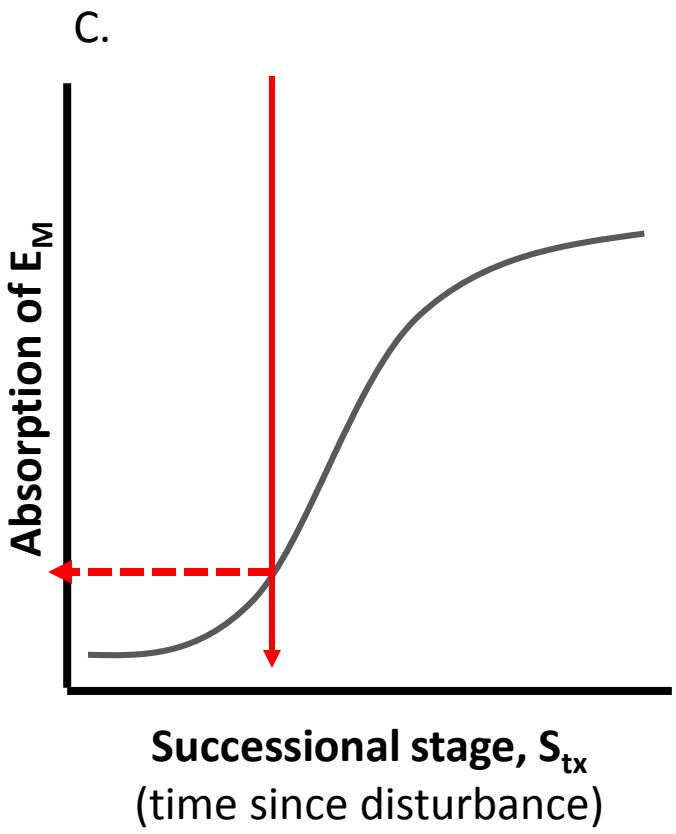

Characteristics of early succession

Metric	Early Succession	Reference
Species richness	↑	Tramer 1975
Biomass allocation to roots	↑	Ewel 1971
Niche complementarity	↑	Odum 1969
Mineral cycles	**open** → **closed**	Odum 1969
Nutrient turnover rates	↓	Vitousek and Reiners 1975

Modified from Hart (1980)

Can we incorporate these properties of later-succession into our annual cropping systems?

Managing for succession

1. **Mimic later-successional processes**

- Reduce succession-initiating factors such as soil disturbance
- Increase crop species richness—niche preemption
- "Perennialize" annual systems—plant perennial crops
- Enhance niche complementarity—intercropping

Managing for succession

2. Reduce need to suppress succession

- Replace “unplanned” plant community with a crop community
- Perennial crops—suppress annuals, improve root growth/foraging capacity and soil niche utilization
- Intercropping—niche preemption, internal nutrient cycling if legumes
- Living mulches—niche preemption, internal nutrient cycling if legumes

Managing for succession

3. **Minimize "negative impacts" of succession**

- Reduce need for management energy (i.e., live with the "unplanned community")
- Capture benefits of compensatory response
- Increase crop tolerance to competition

Take home messages (again)

1. Ecological succession theory and thermodynamics provide useful frameworks for conceptualizing agroecosystems

2. Annual cropping systems represent a state of perpetual early secondary succession

3. Maintenance of this successional state requires energy inputs, usually in the form of synthetic herbicides or physical disturbance

Take home messages (again)

4. Under a succession-energy framework, the negative environmental impacts of weed control and fertilizer application are related to the amount of management energy required to maintain an area of soil in a state of initial secondary succession

5. Additional negative environmental impacts occur as a result of our ability to undermine ecological succession processes

6. Practices that mimic or promote early successional processes will reduce the overall environmental impacts of annual crop production

Obrigado!
E ate' mais

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