TYPES OF BIOMASS

Almost all carbon markets currently consider only carbon sequestration in aboveground biomass, likely because it's possible to visually estimate it – either by "timber cruising" (a forester does an on-site evaluation) or, increasingly, using satellite or aerial imagery.

Belowground biomass is rarely quantified for carbon markets. It's currently impossible to see it for quantification (perhaps ground-penetrating radar/x-ray/other technologies will change that in the future), and the ratio between aboveground and belowground biomass ("root-shoot ratio") is hard to predict and very contingent on the resources available at a particular site. For example, lack of water in a particular area (like a hilltop) would cause plants located in that spot to grow more root biomass than shoot biomass. Because these factors change on a meter-by-meter basis, it is nearly impossible to have enough information to make reliable predictions about belowground biomass that are precise enough for a carbon market.

> One important difference between farming in an agricultural sense versus the management of natural ecosystems (with rangeland likely falling closer to the "natural ecosystems" side of the spectrum and tree plantations likely falling towards the agricultural side) is the degree of standardization and control that the manager has over the system. Farmers and crop scientists generally plow, fertilize, irrigate, and in some cases use temperature control mechanisms to create a uniform environment that contains an excess of water and nutrients. This enables a certain predictability and uniformity of plant growth and yield.
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> Managers of more natural ecosystems tend to take a more scatter-shot approach, expecting plants to establish successfully only in favorable "microsites", or that they will establish and stay small until a good rain year or some other favorable event takes place. Land managers in these systems tend to focus on maintaining "ecological processes" and "ecological functions" (like promoting or excluding grazers, restoring streamflow, using prescribed fire) rather than cultivating specific plants or making sure that they have uniform conditions. The assumption is that plants will grow where or when favorable, and other species may disperse in to fill in the gaps.

ARID LANDS AND THE IMPORTANCE OF SCALE

The type of ecosystem in question is usually described as "semi-arid", meaning that it's dry enough that it can only support small plants like grasses and shrubs. The **water limitation inherently makes it a "low productivity" system**, where productivity refers to the ability for plants to take energy from the sun and turn it into biomass. Relatedly, soils tend to be poorer because there isn't as much of an input of organic matter (dead biomass) or other soil-forming processes that might occur in higher-productivity ecosystems. As a result of all of these factors, plants in semi-arid ecosystems tend to be small and sparse.

The key to carbon sequestration in arid or semi-arid ecosystems is scale, as each acre of land only stores a small amount of carbon. Carbon offsets historically have been focused on productive forests because they have the highest per-acre carbon sequestration, which balances the high costs of administering the offset. Focusing on a low-productivity (low biomass per acre) zone will substantially change the payoff structure.

Under the assumption that scale is a driving factor, **it will be useful to focus on species that have a broad geographic range**. While a rare species might have a molecular structure or other characteristic that is attractive for carbon sequestration, it most likely has extremely specific habitat requirements; this would limit the geographic range or scale of the proposed business. When scale is the goal, it's important to focus on species that are able to operate in many different regions under many different circumstances.

Genetics and climatic tolerances

Many species have different "varieties" or subspecies; these are groups that genetically similar enough to be considered a single species but may be specifically adapted to different environments ("ecotypes") or have been bred for specific traits ("cultivars"). This is especially the case for the widespread species that I attempted to focus on. In terms of planting, **it will almost always be more successful to plant a local variety compared with planting a single variety across the entire species range**; however, I assume that any genomic research for carbon sequestration will be readily applicable across all ecotypes/cultivars/varieties due to their genetic similarity.

COMMON THREATS

Wildfires

Wildfires lead to immediate and long-term carbon "reversals". The immediate reversal occurs when biomass is combusted and released to the atmosphere as carbon or other types of emissions, and the long-term emission occurs when fire-killed but non-combusted biomass gradually decomposes.

All aboveground biomass is vulnerable to wildfire, whether it's live or dead or what its chemical composition may be. While lignin may be slow to decompose, it could easily be combusted in a fire. Belowground carbon may be somewhat protected, because fires tend to move quickly in these ecosystems and soil acts as a good insulator.

It is hard to predict how frequently wildfires will occur in the future. In some ecosystems in the 10-20" precipitation range of the Western U.S., fires occur every 20-40 years. In many others, they occur every 100 years or more. Much of this depends on how productive the ecosystem is because biomass acts as "fuel" that carries wildfire. For this reason, a slightly wetter site can be higher productivity, generate more fuels, and burn more often than an equivalent drier site with nearly the same species mix. Fires are also becoming more frequent as invasive species change the amount of fuel on the landscape. Cheatgrass, in particular, has become prevalent throughout the Western U.S. and is thought to have increased the frequency of fires by acting as a continuous, flammable "fuel" that carries fire in an otherwise sparse landscape.

Given the risk of wildfires, it may be wise to focus on species that can resprout. In these cases, a fire may kill all of the aboveground biomass ("top kill"), but the plant can grow again from the root mass. Many species have this adaptation to wildfires. Another common adaptation is for species to regrow from seeds. The upside of this strategy is that there may be a large number of seeds in the soil, allowing the plant to bounce back across a broad area. The downside is that growth will likely be much slower than if the plant was able to use resources already stored in roots; it will likely take much longer for an ecosystem to reach a pre-wildfire level of biomass.

Drought

Many semi-arid plant species have some sort of adaptation for drought, including leaf and stem systems that prevent the loss of water. However, one important adaptation is that plants may slow their growth or partially die off in dry years but resprout, regrow, reproduce, or otherwise time important biological processes for wet years. Therefore, die-back is a much bigger concern than die-off. Die-back likely won't lead to an immediate reversal, because the dead biomass will still be present on the ground or underground.

Invasive species

Invasive species need to be considered during any species-selection process in semi-arid ecosystems of the Western U.S. Annual grasses like cheatgrass (*Bromus tectorum*) and medusahead (*Taeniatherum caput-medusae*) have become ubiquitous throughout the region – sometimes to the detriment of native species. Several shrub and perennial grass species are unable to germinate and establish if these invasive grasses are around: the invasives might take up all of the available water, create a thatch layer that's hard to break through, or create excessive shade. Many native species can tolerate the invasive species as long as they are already established with a sufficient root system to compete.

Invasive species also change the amount of fuel on the landscape and can increase the risk of wildfire. If fire-intolerant species are selected, it will be necessary to take additional steps to remove invasive species.

> Invasive species are conceptually similar to weeds in agricultural fields, and theoretically they can be treated in similar ways (e.g., herbicide). However, just as with irrigation and fertilizer, it will be very difficult to remove the weedy, invasive species across a big landscape to create ideal growing conditions. Land managers have somewhat "given up" on cheatgrass and medusahead because they are so prevalent and hard to remove. Any planting effort should be undertaken with the expectation that invasive grass seeds will be constantly arriving to the site and potentially interfering with young plants.

Disease / pests

Diseases and other pests, like invasive species, are hard to manage once present. But they tend to be fairly rare or generally inconsequential, as plants tend to be fairly sparse and the moisture-limited environment is generally inhospitable to fungal pathogens. Biological control agents (for example, beetles that target a particular pest) tend to be used in low- to no-management ecosystems; however, it's fairly rare to find a good candidate let alone one that passes regulatory and planning review.

Grazers

Much of the literature on semi-arid plants in the Western U.S. pertains to palatability for and impact of livestock grazers; in fact, some of the candidate species may be compatible with ongoing grazing once plants are established. It's unlikely—but still possible—that non-livestock grazers (deer, etc.) will a large enough impact to warrant consideration during plant selection.

TRADEOFFS AND COMMON PLANT STRATEGIES

Plants have different strategies for dealing with resource limitations and "threats" like wildfire or new competitors. There is no "having it all" in biology; species tend to either invest their energy in fast reproduction (e.g., annual species) or invest their energy to become long-lived – or somewhere in-between. This tradeoff is present even among the focal species for this report, which are exclusively perennial species:

- Some species specialize in "early-seral" ecosystems (just after an event that opens up the ecosystem, like a wildfire, landslide, or a road cut). These plants tend to grow very quickly, but they may be outcompeted within a decade by other plants that invest more in root growth or other mechanisms for long-term survival.
  - E.g., Yellow rabbitbrush (*Chrysothamnus viscidiflorus*)
- Some species specialize in long-term survival. These are often species that have higher amounts of structural biomass (higher lignin) and/or deeper roots. However, these species are often slow-growing and especially slow to establish in new locations.
  - E.g., Big sagebrush (*Artemisia tridentata, Poa secunda*)
- Several species are adapted to the uniquely inhospitable soils present in many semi-arid landscapes. This is beneficial where those soils are actually present, but it can be a cost elsewhere if they are competing with species that have other strategies.

In agriculture, many of these tradeoffs are extremely mitigated because plants are given the resources that they need to thrive and because lifespan is not a primary management objective. In semi-arid landscapes, however, it may be necessary to choose one or more plants in part on the expected level of care and the expected threats. For example:

- If it's expected that plants will be cleared every 10-20 years (either because it's a wildfire-prone area or as an intentional management strategy), it will be best to focus on an early-seral species.
- If carbon sequestration is expected quickly, it may be best to focus on an early species.
- If minimal intervention and maintenance is planned and if the sequestration time horizon is longer, it may be best to focus on the slower-growing but larger species.

An ideal strategy would be to plan on many species and mimic a natural ecological succession, where a set of early-seral species is present at first but later replaced by other later-seral species. **If a single species must be chosen, however, it will be necessary to decide whether the ecosystem is likely to be primarily in an open, early-seral state or primarily in an undisturbed, later-seral state.**