A Comparison of Carbon Cycling and the Surface Energy Balance between Native Perennial and Exotic Annual Grass Communities in Northern Coastal California

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Summary

Grassland ecosystems of California's Coastal and Central Valley regions have undergone dramatic changes, with the almost complete replacement of native perennial grasses by exotic annuals. Our research compares the ecosystem properties and processes that govern the exchange of carbon, water, and energy in California grasslands before and after the invasion of exotic annual grasses at two sites in northern coastal California. To perform these comparisons, we make use of coastal research sites in which native vegetation is found growing alongside locations that have undergone exotic invasion. The broader goal is to understand how shifts in plant community composition can affect global climate change through 1. shifting the balance of carbon storage between terrestrial stocks and the atmosphere, and 2. altering the water and energy regimes that heat or cool the earth's surface.

Our preliminary results indicate that soil carbon storage, the primary carbon stock in these grassland ecosystems is greater in regions dominated by native perennial grass communities. At a site near Bolinas, CA, we found that exotic grass invasion has resulted in a transfer of 50 metric tons of carbon per hectare from the soil to the atmosphere. Over the years 2004–2006, we found energy partitioning into latent and sensible heat fluxes similar among annual and perennial grasses during the portions of the year when water is not limited. When water becomes scarce in the late spring, however, annual grasses die, but the more deeply rooted perennial grasses persist by exploiting deep soil water reserves. Because native perennials remain active, they devote more energy towards latent heat flux and less towards sensible heat flux relative to exotic annuals. During the dry summer months, this difference in energy partitioning and surface drying can lead to soil temperatures of up to 4°C higher in exotic annual communities, but may not appreciably affect air temperatures. Lower albedo, and thus higher energy capture in exotic annuals during the summer months, can raise surface temperatures an additional 6°C relative to native perennials. In sum, this study reveals that the invasion of exotic annual grasses has contributed to both global and local warming in California grasslands.

Key Words: biological invasion, carbon cycle, surface energy balance, global climate change, California grassland

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Objectives

The primary objectives of this research were to determine how a shift in grassland community dominance from native perennial to exotic annual grass communities has affected climate, and to understand the mechanisms controlling climatic changes.

Our questions addressed:

- How does the replacement of native perennial grasses by exotic annuals from Europe enhance or reduce global climate change via a change in ecosystem carbon storage?
- How does the replacement of native perennial grasses by exotic annuals affect the grassland surface energy balance?
- How does the replacement of native perennial grasses by exotic annuals affect surface albedo?

Approach and Procedures

We established research plots at two coastally influenced research sites in Marin County, California, in locations of relatively pure native perennial and exotic annual grass communities. The first site is located in the headlands above Tennessee Valley toward the southern end of the Golden Gate National Recreation Area. The second site is located on the private Bolinas Lagoon Preserve, just outside of Bolinas, CA. In each plot, we measured soil carbon; the major stock of carbon in these ecosystems, to 50-cm depth in 10-cm intervals. To gain a mechanistic understanding of the factors that control soil carbon accumulation, we measured carbon inputs and outputs, including above and belowground productivity, rates of root and litter turnover, root and litter quality and soil respiration. To determine the influence of soil climate on rates of plant tissue decomposition and microbial respiration, we recorded soil temperature to data loggers in each plot at three soil depths and at the soil surface and measured soil moisture periodically at six soil depths. To isolate the role of plants from other factors that influence soil carbon accumulation, we also measured soil porosity, soil pH and soil texture. To aid in interpretation of plant → soil → atmosphere interactions, we performed a soil density fractionation and a C14 analysis.

At the Tennessee Valley field site, we also investigated the influence of a shift in grass community on the components of the surface energy balance. In two locations; one dominated by native perennial grasses and the other by exotic annuals, we erected sets of micro-meteorological sensors to measure net radiation, PAR albedo, relative humidity, soil heat flux, soil temperature at three soil depths, air temperature, soil moisture, and sensible heat flux. We used both the surface renewal (Paw U et al. 1995: Spano et al. 2000) and eddy covariance methods (Baldocchi et al. 1988) to determine the energy balance components. We used linear regression, analysis of variance and analysis of covariance statistical methods and matlab software for data analyses.

Results

Our investigation revealed that differences between native perennial and exotic annual grass communities in habit, function, and morphology resulted in differences in ecosystem carbon storage and cycling. We found significant differences in soil carbon storage at the Bolinas...
Lagoon Preserve site, with greater differences occurring at greater soil depths between the two grass types (fig. 1). Results from the Tennessee Valley site did not reveal a statistically significant drop in soil carbon after the invasion of exotic grasses for the entire 50-cm depth. However, we did find a similar pattern at both sites of greater carbon loss after exotic invasion deeper in the soil profile (fig. 2).

**Figure 1.** Total soil carbon in 10-cm depth intervals in native perennial and exotic annual grass communities at the Bolinas Lagoon Preserve Field Site. Bars represent mean plot values (+1 SE). Different letters represent significant differences (P<0.05).

Our research also demonstrates that the invasion of exotic annual grasses has lead to important differences in the way California’s grassland ecosystems exchange water and energy at the ground surface. We found that radiation capture by the sparser annual grass community is greater (and albedo is lower) than in the flatter, denser perennials over most of the year. This pattern of lower albedo holds over the annual cycle, except for a short period in the spring when
annual grass albedo exceeds that of perennial grasses (fig. 4). Our investigation also revealed that latent heat flux is lower and sensible heat flux is higher in annual grass communities relative to perennials during the period of summer drought, after annual grasses have senesced (fig. 3).

Figure 2. Total soil carbon in 10-cm depth intervals in native perennial and exotic annual grass communities at the Tennessee Valley Field Site. Bars represent mean plot values (+1 SE). Different letters represent significant differences (P<0.05).

Overall, we have found that changes in the cycling of carbon, water and energy brought about by exotic grass invasion have enhanced both global and local warming. The loss of carbon from terrestrial storage where exotic grasses have invaded indicates a transfer of carbon to the atmosphere, where it behaves as a greenhouse gas. Similarly, the lower albedo of annual grasses causes greater radiation absorption at the ground surface in annual grass ecosystems and higher soil and air temperatures. A shift in energy partitioning from latent to sensible heat flux during the hot summer months also leads to an elevation in soil temperatures. Air temperatures may not
be affected, however, because conditions favoring greater sensible heat flux tend to be accompanied by a higher atmospheric boundary layer, which mitigates the addition of sensible heat (Stull 1988).

**Figure 3.** Sensible and latent heat flux for native perennial and exotic annual grass communities over the course of one typical hot summer day, July 20, 2005. Midday, sensible heat flux is higher and latent heat flux is lower in exotic annual grass communities relative to native perennial grass communities.
Discussion

The goals of our research are to understand how shifts in plant community composition may affect global climate change via changes in carbon cycling and storage, and in the biophysics of the land surface. Land cover change resulting from multiple environmental pressures is altering the character and functioning of the earth's ecosystems. Concerns about global climate change necessitate understanding how vegetation shifts affect the regulation of the processes that affect temperature, and these include the water, carbon, and energy cycles. The near extirpation of native perennial grasses by the invasion of exotic annuals across 10 million acres of grassland habitat in California is among the most dramatic of worldwide land cover changes and is the subject of our investigation.
Native perennial and exotic annual grasses cycle carbon, water, and energy differently, due to the unique strategies each employs to survive summer drought. Each strategy involves a set of traits that are of importance to carbon accumulation in soils through their effects on plant productivity, plant tissue quality and heterotrophic respiration, which is in turn influenced by soil moisture and temperature. Perennial grasses employ a drought-survival strategy. Traits that stem from this strategy which also influence soil carbon include 1) the construction of long-lived, recalcitrant tissues that decompose slowly, 2) deep roots that deposit organic matter in which microbes are few and cool temperatures inhibit decomposition, and 3) dense, bunchy aboveground structures that shade the soil surface, thereby reducing surface heating and inhibiting evaporation. In contrast, exotic grasses employ a drought-avoidance strategy. They grow from seed each year when autumn rains begin, set seed and die with the onset of summer drought. Annual grass traits that influence soil carbon include a shallow root system, labile plant tissues, and tall, relatively sparse aboveground structures that allow for higher energy capture, and greater penetration of heat to the soil surface, leading to higher rates of soil evaporation.

**Carbon Cycling**

Our findings indicate that several of the plant traits that we initially hypothesized would differ between native perennial and exotic annual grasses in ways that might influence soil carbon storage do indeed differ, while others do not. At both of our field sites, native perennial grasses were found to produce more root biomass than exotic annuals and to deposit more root litter deeper in the soil profile than exotic annuals, although our findings were not the same for all species. Root litter for perennial grasses is also more recalcitrant than that of annual grasses and may contribute to carbon differences. Aboveground plant traits differed less between grass types than expected, however. In 2004, a relatively dry year, aboveground productivity did not differ significantly between annual and perennial grasses. Yet in 2005, a year in which rainfall was relatively high and persisted into the late spring, annual grasses produced greater aboveground biomass than perennials at the Bolinas Lagoon Preserve field site, but did not differ at Tennessee Valley. At both sites, both a litter decomposition experiment and an analysis of secondary chemical composition failed to turn up significant differences in aboveground litter quality.

The finding that perennial grasses have more recalcitrant root tissues than annual grasses, but do not differ in aboveground litter quality, can be understood from considerations of energy expenditures for plant tissue synthesis. More lignified, more recalcitrant root structures require greater energy expenditures for tissue construction (Mooney and Gulmon 1982; Williams et al. 1989). In the case of perennial grasses, which possess root structures that can live multiple years, that cost is warranted by the greater protection more lignified tissues provide against soil predation and physical weathering. In annual grasses, the construction of more labile and easily synthesized root structures is a strategy consistent with tissues that live less than a single year. This is true for the aboveground leaf tissues of both annual and perennial grasses as well, which also live less than one year. Differences in root productivity and in root tissue recalcitrance are likely contributors to the greater amounts of soil carbon found at the Bolinas field site in locations of perennial grasses.

In addition to differences in the amount and quality of plant tissues, we uncovered significant seasonal differences in the locations, timings and amount of soil moisture between annual and perennial grasses, which in turn caused differences in soil temperature. Although this analysis
remains ongoing, we expect to find that these differences influence soil respiration, and thus soil carbon stocks. Most annual grass roots are highly concentrated in the top 20 cm of the soil profile. Their aboveground structures are sparser than in perennial grasses and allow radiation to penetrate the soil surface. Together, these traits lead to a very dry surface layer in soils that support annual grasses during the period after rains end in the spring. Moreover, the lack of root penetration into deeper soil layers accounts for reserves of soil moisture below the rooting zone. In contrast, the dense, bunchy structure of perennial grasses helps retain moisture in topsoil layers by reducing evaporation. Perennial roots extend deeper into the soil profile and continue to transpire until late in the summer when they enter a period of dormancy. Along the coast, perennial grasses are also known to harvest fog, thus partially replenishing dwindling moisture reserves during dry summer months (Corbin et al. 2005). These differences in the location and timing of soil moisture and temperature between the two grass types should help account for both the differences and similarities we found in soil carbon storage.

**The Surface Energy Balance**

Our research also demonstrates that divergence in plant strategies leads to important differences in the exchange of water and energy between native perennial and exotic annual grasses. These processes are tightly coupled to the carbon cycle and exert a strong influence over climate at the earth's surface. Over the course of the year, both grass types are continually changing in color and structure as they progress through the stages of growth and senescence. These changes produce different optical properties, affecting the amount of radiation that is absorbed and reflected, as is observed in figure 3. This figure documents albedo for the year 2005 in the photosynthetically active range. Over the course of the investigation, we found that because exotic annual grasses are sparser and taller than perennials while in their growth phase, more light is captured by the annual grass canopy. In contrast, perennial grasses remain mainly low to the ground and their dense surfaces are more reflective, thus leading to a higher albedo than that of annual grasses. Annual grasses become more reflective, however, late in the summer when their aboveground tissue flop over. In both perennial and annual grasses, changes in albedo are easily observed as a result of growth and change of color with seasonal changes. The net result is that perennial grasses have a higher albedo for most of the year, and therefore capture less radiation, leading to cooler surface temperatures.

Lastly, we found that a shift from perennial to annual grass communities affects energy partitioning between latent and sensible heat flux after the onset of summer drought. During the rainy season, annual and perennial grasses evaporate similar amounts, despite their different rooting structures. Their rates of sensible heat flux are also similar. However, when water becomes limiting, annual grasses die, while perennial grasses persist by drawing on soil moisture reserves from deep soil layers (Dyer and Rice 1999; Holmes and Rice 1996). After root depth, transpiration in annual grass ceases, evaporation slows and energy partitioning is increasingly in the form of sensible heat. In perennial grasses, this shift is more gradual as some roots remain active. Therefore, during the hot summer months, perennial grasses exhibit a higher ratio of latent to sensible heat flux than do exotic annuals. As a result, locations where annual grasses are found have hotter and drier soil surfaces during the portion of the year when soil moisture is limiting.
In sum, our research demonstrates that the displacement of native perennial by exotic annual grass ecosystems in California has advanced both local and global warming via changes in carbon biogeochemistry and micro-meteorology. Our research is of importance to the Kearney mission because it provides an in-depth examination of the factors affecting soil carbon in a major California ecosystem impacted by biological invasion. Moreover, our findings are relevant to policy makers because it provides impetus for restoration of a unique California ecosystem by linking restoration objectives to climate change goals.

References


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