ECOSYSTEM FUNCTIONING in HISTORICALLY FARMED WETLANDS

Lopez Island, WA

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April 2011

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SUMMARY

The objectives of this study were to develop meaningful indicators of ecosystem functioning; to evaluate conventional and alternative farming methods in the islands with respect to their impacts on wetland functioning and prey production; and to compare the ecological consequences of abandonment of wetland farms (and *e.g.* their acquisition by a land conservancy) with the adoption of alternative farming practices developed at Sweet Grass Farm, Lopez Island, WA. A key consideration was the extent to which agriculture has historically been focused in depressional wetlands in the San Juan Islands, and is now facing greater legal restrictions at the same time as public demand for locally grown food increases.

Data were collected in 2009 and 2010 from two management units at Sweet Grass Farm and 12 other Lopez Island wetlands classified as conventionally farmed, historically farmed but abandoned, or relatively undisturbed. Data include soils, root biomass, plant communities, dissolved nutrients (nitrogen, phosphorus, carbon), and the abundance and diversity of aquatic and terrestrial invertebrates during the growing season.

Dissolved nutrients were consistently greatest at Sweet Grass Farm. Aquatic and terrestrial invertebrates were most abundant at Sweet Grass Farm in 2009, and tied with a long-abandoned farm and recharged wetland in 2010. Invertebrate diversity was at least as great at Sweet Grass Farm as other study sites, including a relatively undisturbed lake and marsh. We conclude that management practices can reconcile continued farming and invertebrate diversity and productivity in the San Juan Islands. Invertebrates form a large part of the prey base for native vertebrates such as salmonids, amphibians, reptiles, birds, and bats. For protection of insectivorous animals, improving farm management is at least as effective as the abandonment of wetland farms.

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Appendix A: Plant communities of study sites

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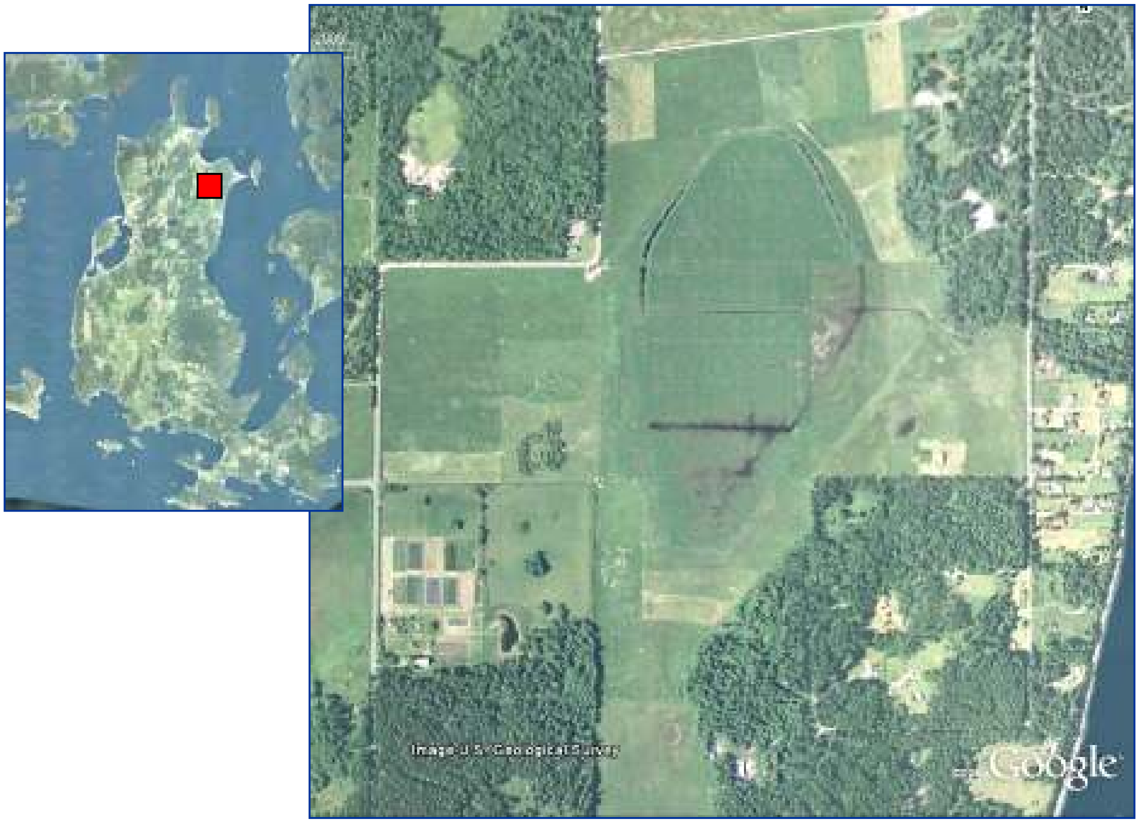
This two-year project explored innovative approaches to revitalizing farming in degraded, long-farmed and pastured wetlands in the San Juan Islands, WA, where most large historical wetlands were shallow vernal pools, and nearly all wetlands greater than five acres in extent have been cropped or used as pastures at some time since 1880. One of our goals was to develop and test inexpensive indicators for comparing the ecological impacts of different farming practices in wetlands. Our other goal was to evaluate some of the practices of one wetland farm, to see how well food production had been balanced with wetland conservation and biodiversity. A core question was whether raising cattle, and feeding juvenile salmon in the nearshore (a function of water quality of production of terrestrial prey favored by salmon) can coexist in island ecosystems.

Study sites

The focus of this project, Sweet Grass Farm, is located on northeast Lopez Island, WA, at the headwaters of a small naturally northward draining watershed (Shoal Bay). A 19th Century drainage ditch diverts overflow water eastward down a short, steep ravine to Lopez Sound, however.

Figure 1: Sweet Grass Farm, Lopez Island, WA



Sweet Grass Farm (SGF) owns or leases about 206 acres of relatively level land perched just above Swifts Bay and Lopez Sound. More than half of this area floods each year, and the distribution of muck and silt loam indicates that the seasonally flooded zone was once even larger. There is historical evidence in the unpublished 1859-1860 field notebooks of naturalist C.B.R. Kennerly that Coast Salish people were burning, clearing and gardening this wetland over 150 years ago. Maps from 1889 show pastures and orchards. The site has produced food continuously for centuries. Today, the valley supports not only SGF but also the largest truck farm on Lopez (Horse Drawn Farms), which extends north of the wetland. Both SGF and Horse Drawn are organic

When the current owner of SGF acquired the land a decade ago, it was reportedly overgrazed, brushy, and marginal. The center of the wetland had been accessible to cattle for decades and was shallow muddy water in winter, and hummocky mud in summer. No distinct wetland habitat or plant community remained, according to the current owner and his neighbors.

Restoration of SGF began with the excavation of a semi-circular canal around the heart of the wetland, and clearing of the original stream channel draining the wetland to nearby Lopez Sound a few hundred yards to the east. A modest control structure made it possible to close and fill the wetland in winter, and slowly but not completely drain it in summer. In 2009 and 2010, we observed over 40 acres of standing water until late spring and 10-20 acres of standing water, mud, rushes and tall grasses in summer. According to the owner, summer wetted acreage has been increasing, and we observed evidence of this in soils and plant distributions, as well as farm records of hayed area.

Reed canary grass is the dominant vascular species in the wetland, as true of most farmed or previously farmed wetlands in the San Juan Islands. Originally introduced as a water-tolerant forage grass for sheep and cattle, to “reclaim” the islands’ wetlands, canary grass is now regarded as an invasive nuisance by farmers as well as restoration ecologists in San Juan County. Reasoning that problem species can be managed by making them resources, SGF began experimenting with mowing and haying the drier portions of the wetland, using fresh young regrowth of canary grass for pasture, and the hay for bedding. SGF was in the third year of this experiment when we began collecting data.

SGF has protected the acreage inside the semicircular canal (the “core wetland”) – active farming has been restricted to the slightly elevated, drier areas outside the canal, as well as shoulder lands that do not have hydric soils and consequently produce shorter and less abundant herbiage. In summer a clear boundary can be seen between a patchwork of electric fences marking small pasture blocks at different stages of rotational grazing, and a dense oval patch of very tall (5-7 feet) intensely green grasses and rushes with abundant nesting and foraging birds.

Just before and during our study, SGF experimented with faster and slower rates of rotation (lighter and more intense grazing), mowing and mulching of different portions of the farmed wetland area. The landowner believes that a combination of relatively slow rotation and mowing (haying rather than mulching) yields the best results in terms of rich young growth and regrowth throughout the season. Our data are consistent.

Comparisons were made between the north and south portions of SGF, because they have been managed differently for a number of years, mainly with regard to rotation rates and the disposition of mown grasses (*e.g.* haying versus mulching). Comparisons were also made between SGF and four conventionally farmed tracts on the same island, two of them still in production and two already abandoned to "go back to nature":

- ☐ Center Pond: topographically and hydrologically a close twin to SGF but located in another drainage several miles distant; some standing water year-round; varied livestock uses for over a century; currently stocked with horses; no management other than removing livestock from the wetland in winter when it is flooded.
- ☐ Davis Farm: originally a salt marsh; impounded by a tide-gate, drained and filled, and used for conventional cattle raising since 1908; some rotational grazing and a relatively low stocking rate under current management (about half the number of animals per acres a SGF). In early 2009 as we were beginning our study, the tide gate failed and the entire farmed area was flooded with seawater for some weeks. We collected data in 2009 but concluded that the residual salinity made this farm no longer usefully comparable to others on Lopez.
- ☐ Chadwick Marsh: drained, farmed and mined for peat up to the 1950s, then burnt and abandoned; year-round standing water; popular with waterfowl hunters. The uplands on the north and east sides of the marsh are conventionally used summer cattle and sheep pastures, but are hydrologically isolated by intervening roads.
- ☐ Hummel Marsh: formed by seasonal overflow of Hummel Lake, a natural glacial kettle, this shallow level wetland drains into a seasonal stream that flows north to Swifts Bay close to SGF; drained and used for livestock from the 1880s to 1950s, then left unmanaged. A small-scale organic seed grower occupies several upland acres, otherwise the nearest agricultural operation is on the far side of the lake.

Table 1: Historical and current use of primary study sites

	Original	*Historical*	*Current*	*Adjacent*
Sweet Grass Farm	Vernal pool	Livestock	Livestock	Livestock, crops
Center pond	Vernal pool	Livestock	Livestock	Hayfields
Chadwick marsh	Vernal pool, bog	Livestock, peat	Hunting	Livestock
Hummel marsh	Drainage way	Livestock	Abandoned	Crops, forest
Davis Farm	Salt marsh	Livestock	Livestock	Livestock

Table 1 summarizes original wetland structures, and historical and current uses of these properties, as well as current uses of adjacent lands. Stocking levels of pastures are comparable at all five sites. None of the sites has the weedy thistle-and-dock community characteristic of overgrazed pastures in the islands; they are all stocked responsibly.

All of our primary study sites are shallow depressions in glacial outwash terraces, with significant organic accumulations toward the center of each basin. Each study site is inundated seasonally. Standing water persists year-round in parts (10-30 percent) of each study site. Annual precipitation averages 20-25 inches throughout the study area.

Table 2: Soils and hydrology of primary study sites

	Basin	*Terrace*	*Perennial water*
Sweet Grass Farm	Shalcar muck	Coveland loam	Ditches, pools
Center pond	Coupeville loam	Coveland loam	Central marsh
Chadwick marsh	Semiahmoo muck	Coveland loam	Central marsh
Hummel marsh	Semiahmoo muck	Coveland loam	Stream channel
Davis Farm	Dugualla muck	Coveland loam	Tidal slough

Terraces are composed chiefly of Coveland loam: a black moderately acidic (pH≈ 6.4) silt loam with small amounts of gravel overlying a mottled dark grayish brown sandy clay loam (Schlots et al. 1962, USDA 2010). Drainage is poor, so a significant portion of rainfall runs off into shallow depressions forming vernal pools and in deeper depressions, such as glacial kettles, natural lakes of which Hummel Lake on Lopez is an example. An accumulation of decaying vegetation gradually forms "mucks" and, in lake bottoms, peat bogs. Orcas Peat can be seen in part of Chadwick marsh, and on the east side of Hummel Lake, where we have drilled through 27 feet of well preserved peat to underlying clays.

Table 3: Composition of topsoil by weight at primary study sites

	% Roots	*% Detritus*	*% Mineral*	*Roots/Detritus*
Sweet Grass Farm N	63	34	3	1.85
Sweet Grass Farm S	56	41	3	1.37
Center pond	60	34	6	1.76
Chadwick marsh	55	31	14	1.77
Hummel marsh	60	10	30	6.00
Davis Farm	48	52	<1	0.92

Lopez Island mucks differ little in basic characteristics. Shalcar muck is typically associated with depressional wetlands on stream terraces or outwash terraces, and reflects the decomposition of woody and herbaceous debris. Semiahmoo muck is also associated with depressions in glacial outwash, with a greater herbaceous contribution and overlying dark grayish brown silty acidic clays (pH≈5.0). Dugualla muck is more representative of natural and relict lagoons and depressions in marine shore complexes. It is dark, fibrous, slightly acidic (pH≈6.5), mottled, with marine shells in lower horizons of the soil profile.

Davis farm is indeed located on what was once a salt marsh, barricaded by a tide gate no later than 1908 in order to expand grazing area.

Center pond lacks a muck component, which may reflect its formation as well as 19th century efforts to deepen it to water livestock. Coupeville loam forms in glacial drift over dense glaciomarine deposits in drainage ways of glacial drift plains. It is a black sandy moderately acidic loam (pH≈5.6), overlying mottled grayish brown angular blocky clay loam. Center pond is part of a relict riparian corridor extending from Lopez Hill to Davis Bay—the largest watershed on Lopez.

Table 3 summarizes data from our analysis of topsoil (root zone) at primary study sites. Areas currently in cattle and horse production have a markedly higher ratio of total organic matter (roots and plant detritus) to mineral grains. The ratio of roots to detritus is greatest at the least disturbed site (Hummel), and lowest at a site suffering from periodic seawater influence (Davis).

In addition to collecting two growing seasons of data at SGF and our four primary comparison sites, we conducted a one-time "blitz" of eight additional wetlands in August 2009 that included residential dug ponds, some with adjacent farmed areas, and relatively undisturbed coastal freshwater and salt water wetlands. Some names have been changed to protect the privacy of the landowners. Ponds were dug 25-75 years ago.

Figure 2: Location of all study sites (primary red, blitz yellow)

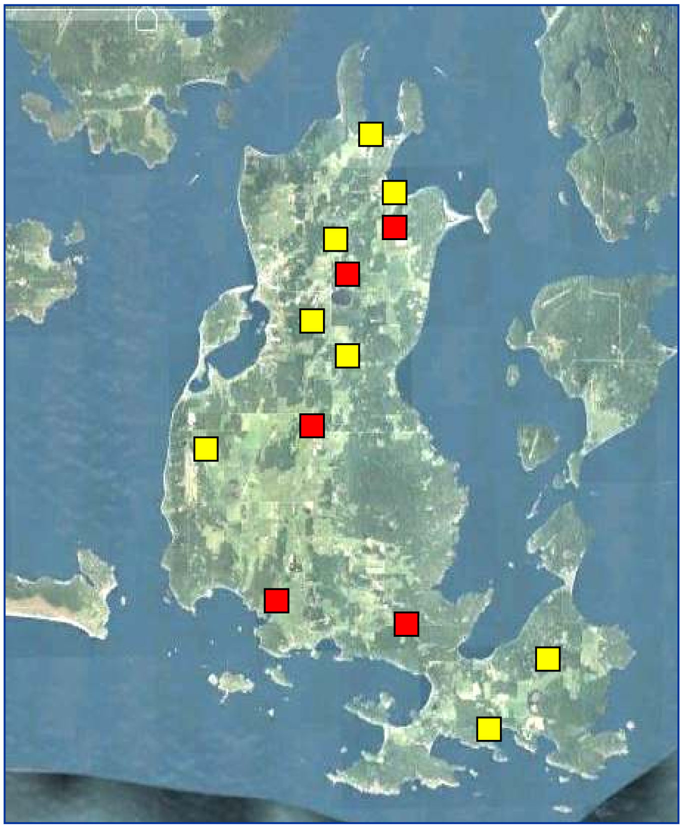


Table 4: Historical and current use of additional study sites

	Original	*Historical*	*Current*	*Adjacent*
Airport Road pond	Vernal pool	Livestock	Dug pond	Airport, hayfields
Aleck Bay marsh	Coastal marsh	Drained, salt hay	Undeveloped	Homes
Sperry Road pond	Wet woodland	Logging	Dug pond	Woodlands
Center Road pond	Wet woodland	Logging	Dug pond	Hayfields
Whiskey Hill pond	Drainage way	Livestock	Dug pond	Hayfields
Crossroads pond	Drainage way	Livestock	Dug pond	Woodlands
Port Stanley lagoon	Coastal lagoon	Drained, salt hay	Salt marsh	Homes
Shoal Bay pond	Drainage way	Livestock	Dug pond	Livestock

All study sites were surveyed to map current plant communities, identify any rare native plants and document invasive plant species. Some plants may also be indicators of nutrient or contaminant loading.

Table 5: Dominant vegetation at all study sites

	Dominant	*Secondary*	*Total species*	*% Exotic*
Sweet Grass Farm N	Canary reed grass		10	40
Sweet Grass Farm S	Canary reed grass		20	65
Center pond	Canary reed grass	Yellow pond lily	10	10
Chadwick marsh	Canary reed grass	Cattail, Slough sedge	19	16
Hummel marsh	Canary reed grass	Cattail	7	29
Davis Farm	Pacific cinquefoil	Canary reed grass	34	56
Airport Road pond	Canary reed grass	Cattail, Mare’s tail	10	10
Aleck Bay marsh	Tule	Cattail	17	18
Sperry Road pond	Red alder	Slough sedge	23	13
Center Road pond	Canary reed grass	Nootka rose	17	18
Whiskey Hill pond	Canary reed grass	Spike rush	17	18
Crossroads pond	Cattail	Red alder	16	12
Port Stanley lagoon	Seashore salt grass	Sea asparagus	7	0
Shoal Bay pond	Willows	Oceanspray	14	14

On the continuum of study sites, Sweet Grass Farm ranks near the middle in terms of plant diversity, and close to the top with regard to non-native species. From a distance it appears to be monolithic Canary reed grass, but closer examination reveals a variety of native forbs forming a kind of understory beneath the invasive grass.

All but one of our primary study sites is dominated by invasive Canary reed grass, associated with historical grazing of vernal pools, mainly (in the islands) by sheep. Tule, cattails, and sedges represent relict native wetland plant communities, while cinquefoil or Sea asparagus (*Salicornia virginica*) represent native salt marsh assemblages. Most sites are almost exclusively herbaceous (grasses and forbs), with only a few copses or edges of water tolerant woody species such as alders, willows, crabapples, and oceanspray. Total plant diversity and the proportion of native plant species varies greatly between sites, as a consequence of land use histories, but with the exception of the two brackish sites (Davis and Port Stanley) there was considerable overlap of the most abundant species.

Some aquatic plant species serve as indicators of nutrient loading; ordinarily they thrive where riparian vascular plants are unable to utilize nutrients in runoff fully. Large and small duckweed are mostly reliably associated with nutrient rich waters. The unusual carnivorous liverwort Purple-fringed riccia, *Ricciocarpus natans*, is also widely regarded as a nutrient indicator. Duckweeds were present at all the primary study sites except for Davis Farm, where there was no standing fresh water. Center pond was especially rich in aquatic species.

Table 6: Aquatic plant indicator species at study sites

	Duckweeds	Pondweeds	Pond lilies	Bladderwort	Liverwort
	Lemnaceae	Potamogeton	Nuphar	Urtricularia	Ricciocarpus
Sweet Grass Farm	X	X			
Center pond	X	X	X	X	
Chadwick marsh	X				
Hummel marsh	X				X
Davis Farm					
Airport Road pond	X	X	X		
Aleck Bay marsh					
Sperry Road pond		X	X		
Center Road pond	X	X			
Whiskey Hill pond		X			
Crossroads pond		X	X		
Port Stanley lagoon					
Shoal Bay pond	X	X		X	

Notwithstanding differences in land use history, primary study sites were similar enough in soil structure and (broadly) in their plant communities, to allow us to focus on the association of different land use practices on wetland animals.

Choosing indicators

Choosing biophysical indicators of wetland functioning is not a trivial task. Basic *processes* such as water recharge, nutrient cycling, accumulation and degradation of plant debris reflect the capacity of a wetland to support organisms; but the history and uses of a wetland can greatly affect the biotic *outcomes*: annual biomass yield, biodiversity and the structure and resilience of the trophic web. Under conditions of limited funding and time, furthermore, it is challenging to find an affordable suite of indicators that are sufficient to answer the questions at hand.

At the outset, then, it is essential to refine the question or hypothesis. What do we mean when we say that a wetland is "healthy"? It is tempting to think in terms of habitat resilience and sustainability, *i.e.* its ability to continue to produce biomass despite stresses such as the development of adjacent lands, and climate change. This requires a long-term data set. It also begs two key questions: Are there limits to resilience even in undisturbed habitats? Is continuous biomass production enough, or does it matter what kind of things comprise the biomass—for example, wheat versus frogs or fish? Biodiversity is a factor in resilience or adaptive capacity, but do we care what species are included, or should we be satisfied with diversity regardless of its composition?

In studying the accommodation of agriculture to wetlands, we have no choice but to regard species composition as relevant, if not central to the analysis. By definition, we want to determine whether a mix of species *that includes human foods* can be sustainable. There is evidence from many parts of the world of small-scale agro systems that co-exist with some of the planet's richest ecosystems. At the same time, food production for most of the world's human population has unquestionably reduced biodiversity and resilience over large areas. The question of *what food production practices minimize diversity loss* has been the focus of a growing number of medium-term studies that assume, implicitly, that food production and ecosystem resilience are not mutually exclusive.

Diversity was long conceived as a single statistic (number of species or *richness*). There are problems with this approach. Richness is not an absolute good for which more is always better. Richness varies, even between relatively undisturbed ecosystems, since resources such as energy, water and nutrients varies between ecosystems. An increase in richness—due, for example, to colonization by new species—does not necessarily result in greater sustainable richness or biomass. Losses of richness at higher trophic levels are less disruptive of trophic webs than losses at lower levels: losing carnivore species is not as disruptive as losing plant diversity (Scherber et al. 2010). Microbial richness is poorly understood and difficult to quantify—genomic tools are increasingly preferred—thus our existing ideas about species richness do not adequately take account of about one-third of planetary biomass.

Insofar as the meaning of richness is influenced by trophic structure as well as the availability of resources, ecologists increasingly pair richness with *evenness*, a measure of the relative proportions of species within an ecosystem.

The present study illustrates another problem with relying on species richness as a measure of ecosystem health: ecosystems are interconnected. Animals and plants tend to disperse to neighboring habitats, where they not only mate and reproduce, but also where they may be important sources of food for other animals and plants. An ecosystem can be resilient to the extent of maintaining its richness and evenness, in broad terms, but not continuing to export the same kinds of food services to its neighbors. Taken in isolation, the ecosystem is adapting and sustaining itself, but at a regional scale, there is a loss that puts stress on other ecosystems.

In the case of the present study, a key consideration from the outset was export of terrestrial prey—chiefly insects—to nearby nearshore salmon nurseries. The objective is not merely to produce human food with minimal adverse impacts on wetland functioning, but to produce human food *and salmon prey* with minimal adverse impacts on wetlands. Wetlands can conceivably survive agriculture through changes in trophic structures that restore overall richness and evenness, at the expense of particular groups of organisms.

Based on these considerations we chose to focus on insects—especially the insect orders and families we have seen utilized locally by salmon (Barsh et al. 2009)—as well as other terrestrial invertebrates such as arachnids and myriapods that can be collected by the same means. Insects and other small invertebrates not provide prey for salmon but also for small mammals (chiefly bats and shrews in the islands), amphibians (four native species documented on Lopez Island), and insectivorous birds—a large portion of Lopez Island's terrestrial vertebrates.

During the first year of this study, each study site was characterized in terms of its geology, hydrology, plant community structure and diversity, root and detrital biomass of its soils. Data were also collected at least monthly on terrestrials and dissolved nutrients (carbon, nitrogen, phosphorus) from April to September. Several methods were tried and compared for sampling insect diversity including pan traps, deadfall traps, kick nets, and sweep nets. Zooplankton were collected by tow-net from spring to early summer, as long as there was sufficient standing water at least a half-meter deep.

For the second season, we focused on insect richness, evenness and abundance for the period of greatest insect activity (June to August). Sampling frequency was increased to weekly, and replicate traps at each site were increased from five to ten. Based on 2009 results, pan traps were used exclusively; they harvested a wider variety of insect families. Our aim was to test our preliminary conclusions on insect diversity and abundance with a larger, more statistically reliable data set.

Birds and bats may also be useful indicators when combined with the richness and diversity of their insect prey. Reliable bird censuses required more fieldwork than insect trapping; we began training local volunteers in bird identification and survey methods in summer 2010 and will have greater capacity to use birds as wetland indicators in the near future. Bat surveys are more problematic. Bat detectors are expensive, especially if they are designed to record at multiple frequencies, and most bat species thus far identified in the islands are in the *Myotis* genus, and are difficult to distinguish from their echolocation frequencies. Amphibians would likewise be useful indicators, as consumers of insects, if adequate field hours could be mobilized. Over the course of two field seasons with teams on the ground for more than 500 hours, we encountered fewer than 50 amphibians—most of them tadpoles of the Pacific chorus frog (*Hyla regilla*) and a few Rough-skinned newts (*Taricha granulosa*).

Methods

Root biomass. Five turf samples were collected at each primary study site on the first day of fieldwork (April 2009) in same areas where insect traps were set. A stainless steel trowel was used to cut and remove 500 cm^2 blocks of soil and roots 15 cm deep and to transfer samples to plastic bags for transportation to our laboratory. Samples from the same site were consolidated, and their combined compressed volume measured in a large graduated cylinder. Consolidated samples were then rinsed in plastic tubs until roots and woody detritus remained to be sorted and dried. All rinse water was sieved to remove the larger organic debris, then separated into organic detritus and mineral grains by flotation. Fractions from each consolidated sample were sun-dried for 24 hours prior to weighing.

Dissolved nutrients. Standing water was collected at each study site in the vicinity of our insect traps (see below) in 250-mL Nalgene bottles. Bottles were rinsed twice with sample water before being filled. Samples were stored on ice in the field and refrigerated overnight at 4^oC prior to testing. Dissolved nitrogen was measured colorimetrically using the zinc reduction method for nitrate, diazotization method for nitrite, and Nesslerization method for ammonia. Dissolved phosphorus as phosphate was measured colorimetrically by the ascorbic acid reduction method. Reagent kits were purchased from LaMotte, Inc. Chestertown, MD). Relative concentrations of dissolved hydrocarbons were measured by UV absorbance at 220 nm for aliphatic species and 254 nm for cyclic species.

Contaminants. Potentially toxic contaminants were estimated by using two proxy measures, both based on the assumption that a large proportion of cyclic hydrocarbons in aquatic ecosytems are anthropogenic in origin. Relative concentrations of cyclic species in neighboring wetlands should reflect anthropogenic inputs such as fuels and lubricating oils and agricultural chemicals. We measured total dissolved cyclic hydrocarbons by the UV absorbance method, and the subset of phenolic hydrocarbons colorimetrically by the antiaminopyrine method (LaMotte, Inc., Chestertown, MD).

Aquatic invertebrates. When standing water was present, we towed an 80-micron mesh freshwater plankton net (150-mm wide) by hand for 15 meters in the vicinity of our insect traps. Contents of the 150-mL collection bottle were then transferred to a glass jar and preserved with 50 mL of ethanol. A non-quantitative benthic sample was also taken with three one-meter sweeps of a D-net through riparian vegetation. D-net samples were far richer in aquatic insect nymphs and mollusks.

Insects and other terrestial invertebrates. In 2009 we deployed five pan traps and five deadfall traps at each site, all within a radius of roughly 15 meters. Pan traps were 6-inch plastic cereal bowls painted bright yellow, filled with a shallow layer of soapy water (changed to 10% boric acid in 2010 to minimize environmental impacts), and tethered to shoreline vegetation by a thin nylon line, or left on relatively open ground weighted with a pebble. Deadfall traps were 8-ounce straight-sided glass jars, buried to their rim in the ground and filled with a shallow layer of soapy water. Traps were set in the morning and collected after 24 hours. Contents of traps were concentrated by pouring through a filter-funnel, then preserved in glass jars with ethanol (final concentration approximately 75%). Pans sometimes overturned by wind or livestock; deadfalls occasionally filled with soil or rainwater. We normalized all catch data to account for variations in total number of traps that functioned properly. An effort was made to attain consistency in the placement and distribution of traps, including a relatively fixed distance from trap to trap

Comparison of yields found that pans were biased (not surprisingly) toward flying and hopping insects, while deadfalls attracted more beetles and arachnids. Total diversity of species was nonetheless greater in the pans. We also observed greater variability than expected amongst the pans deployed at the same site. To improve reliability in 2010, we used pans alone, and deployed ten pans at each site rather than five. This sacrificed data on arachnid abundance, but little useful data were lost for Coleoptera, which were scarce and not very diverse in either deadfalls or pans. Eliminating deadfalls made laboratory work less tedious, because deadfall contents were often muddy and difficult to sort.

We also explored the effects of trap placement on results. In August 2009 we put additional pan traps in tall grass rather than relatively open ground at several sites. These "deep" traps attracted proportionally more wasps and aphids, but abundance and diversity as a whole were lower. In 2010 we accordingly restricted all traps to open ground.

In 2009, traps were set every month in spring and every second week in summer, for a total of eight collections over six calendar months. In 2010 sampling frequency was doubled to weekly for greater reliability, but also restricted to the period of greatest insect abundance (June, July, August) for a total of eight collections over three months. Change in sampling frequency and the number of traps set on each sampling date, mean that 2010 data permit finer-scale analysis of insect diversity.

Results

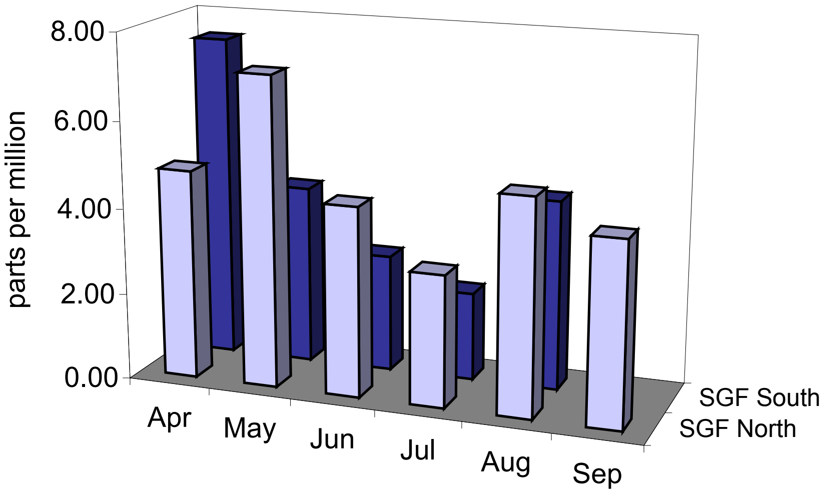
1. Dissolved nutrients

On the whole, plants and algae that require nitrates for protein synthesis must be in balance with bacteria that produce nitrates from ammonia (in decomposing animal and plant material) or elemental nitrogen. A surplus of nitrates results in accelerated growth of plants, algae, and denitrifying bacteria, while a surplus of ammonia from decomposing organisms leads to blooms of nitrifying bacteria. In the long term, nitrogen compounds should not accumulate in waters or soils unless something interferes with the abundance and diversity of bacteria.

Humans, cattle, horses, sheep and other mammals excrete surplus nitrogen in the form of urea and ammonia. Urea breaks down in water to ammonia. Elevated ammonia is therefore characteristic of livestock operations. In a balanced soil ecosystem, a surplus of ammonia feeds nitrifying bacteria, which in turn produce nitrates taken up by vascular plants that—eventually—feed animals and humans, completing the cycle.

Soil nitrogen cycling is affected by excessive loading: increased inputs of animal waste, nitrogenous fertilizers, or accelerated plant death and decomposition, all of which are associated with agriculture. Toxic chemicals used in agriculture can kill bacteria and reduce the nitrogen processing capacity of soil. If farming practices overwhelm bacterial capacity, available nitrogen increases in water, favoring algae and bacteria over vascular plants. Nitrogen surplus can be short-term or seasonal, but only indicates a problem if it persists and is accompanied by a shift in biomass from plants to algae and bacteria.

Figure 3: Total nitrogen by month, 2009
Sweet Grass Farm



Total dissolved nitrogen varies over the growing season (Figure 3). Nitrogenous compounds generally accumulate in winter when plant growth is at a minimum, and the effect is greatest in wetlands as rain runoff transports silt, detritus and nutrients into the wetland from surrounding homes, gardens, and pastures. Spring and early summer plant growth in spring gradually draws down the nutrient stock, on the whole. However as can be seen at Sweet Grass Farm, nutrient spikes can result from spring grazing, and summer mowing and grazing, which converts live standing vegetation into detritus and manure.

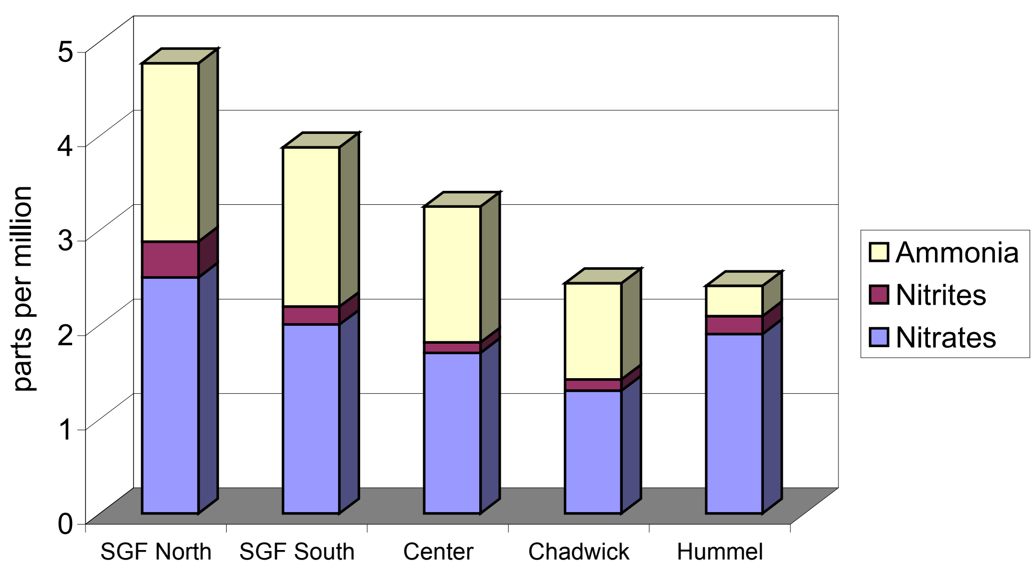


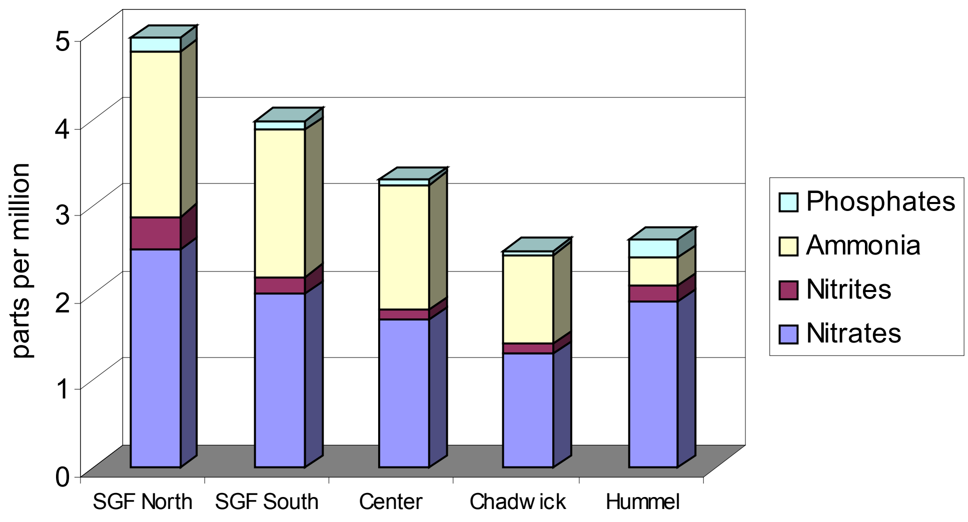
Figure 4: Mean total nitrogen, 2009 season

The compartmentalization of dissolved nitrogen at our primary study sites (Figure 4) reflects current land uses, with ammonia forming a significantly greater proportion of total nitrogen at the sites where livestock routinely graze. Nitrates are a larger proportion at Hummel marsh, where nitrogenous compounds necessarily arise chiefly from decaying vegetation. Davis Farm is omitted because fresh water sampling opportunities could not be found throughout the season.

Figure 4 also introduces an important finding of our study: dissolved nitrogen was significantly elevated at Sweet Grass Farm in comparison with other study sites. This is a predictable consequence of intensive use of the dominant vegetation of the SGF wetland, Canary reed grass, for cattle grazing and hay production. Much of the nutrient surplus disappears by fall, presumably as vascular plant growth, including renewal of the Canary reed grass, supporting nutrient-loving aquatic plant species such as duckweeds, and algae that feed large spring aggregations of zooplankton and aquatic insect larvae.

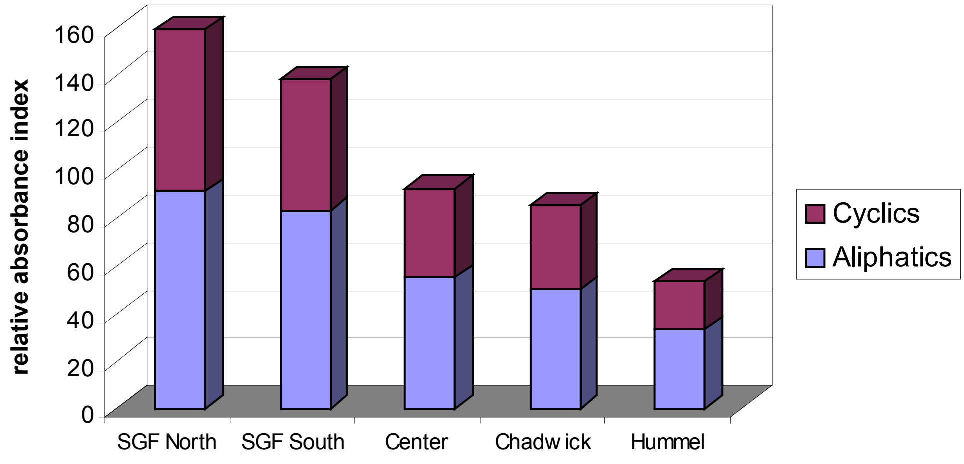
Phosphorus is much less available than nitrogen at our study sites (Figure 5). The highest concentrations of phosphates over the course of the 2009 growing season were at Sweet Grass Farm and the Hummel marsh, where large seasonal aggregations of Canada geese may be a factor. Chemical fertilizers are not applied to any of the study sites, thus dissolved phosphates must be derived from soil minerals or imported by wildlife. Island soils are young and mainly derived from glaciomarine sediments—which can be enriched in phosphorus—or glacial till.

Figure 5: Mean total nutrients, 2009 season



Dissolved organic carbon (DOC) is a nutrient for microorganisms that cannot use atmospheric carbon dioxide, or consuming other living organisms as their carbon source. DOC is also a useful indicator of biological activity in wetlands, since it is created by the decomposition of plants and other organisms, and “cleared” by the microbial and fungal communities that are essential to the recycling of all macro- and micronutrients in waters and soils. DOC is also relatively simple to measure spectrophotometrically since carbon-to-carbon bonds absorb ultraviolet light selectively in the range of 200-260 nm.

Figure 6: Mean dissolved hydrocarbons
2009 season



It is useful to distinguish between dissolved aliphatic (simple chain) hydrocarbons that absorb selectively at 200-220 nm, such as fatty acids, sugars, starches, and cellulose; and cyclic hydrocarbons that absorb at 254 nm. Cyclic hydrocarbons include naturally-occurring and synthetic bioactive compounds ranging from hormones to pesticides.

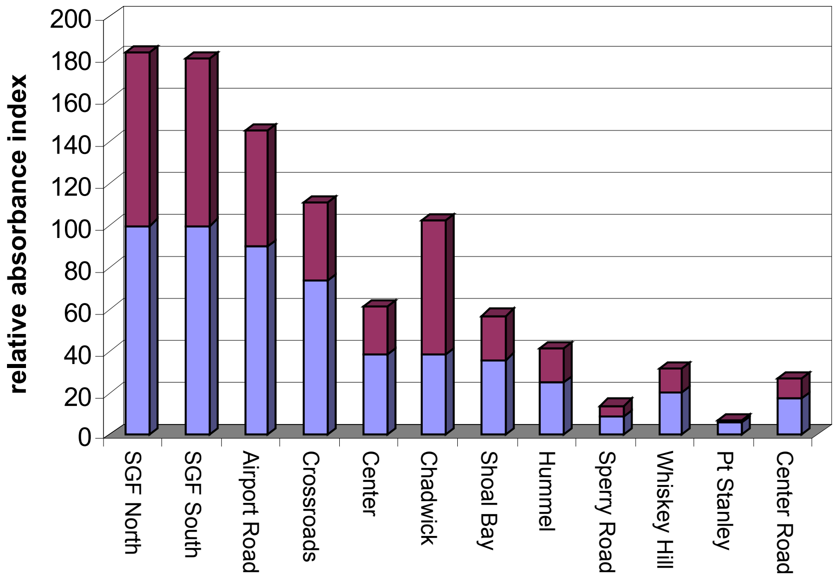


Figure 7: Total dissolved hydrocarbons
27 August 2009

DOC differed markedly across our study sites in 2009 (Figure 7), indicating the usefulness of this water quality parameter for detecting differences in land use practices within a relatively uniform geophysical landscape.

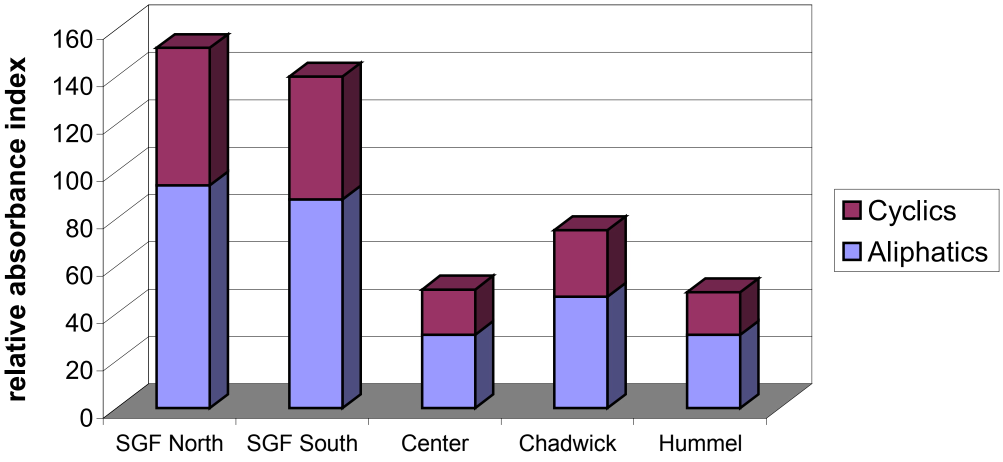


Figure 8: Mean dissolved hydrocarbons
2010 season

DOC relationships among our primary study sites were similar in 2009 and 2010, moreover, suggesting that practices at Sweet Grass Farm have a consistent and persistent effect on carbon recycling and plant growth (Figures 6 and 8). Reduced livestock loading at Center pond may explain the decrease in DOC there from 2009 to 2010.

Consistent relationships were obtained by measuring total phenols (simple cyclic hydrocarbons) by an alternative spectrophotometric method. For the 2009 season, total phenols at Sweet Grass Farm averaged 0.38 parts per million in water, roughly twice the mean results for Center pond (0.22 ppm), Chadwick (0.19 ppm) and Hummel (0.21 ppm). These results are consistent with differing levels of organic turnover from decomposition of plants and animal waste, and do not imply contamination by (for example) petroleum-based products or agricultural chemicals. DOC results were also broadly consistent with chlorophyll concentrations in water (Figure 9), indicating that differences in DOC mainly reflect differences in plant growth and decomposition.

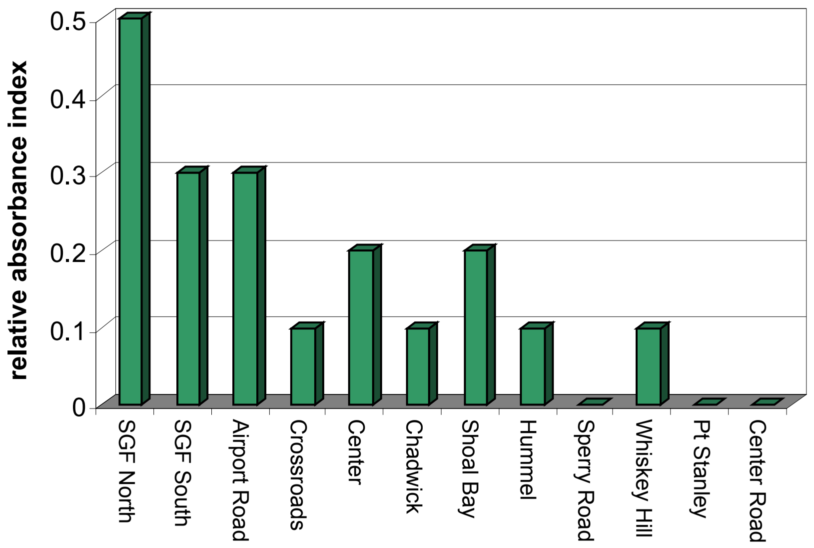


Figure 9: Chlorophyll concentration in water
27 August 2009

Fecal coliform counts were relatively low at Sweet Grass Farm (season mean 13), compared with Center pond (85) and Hummel (42).

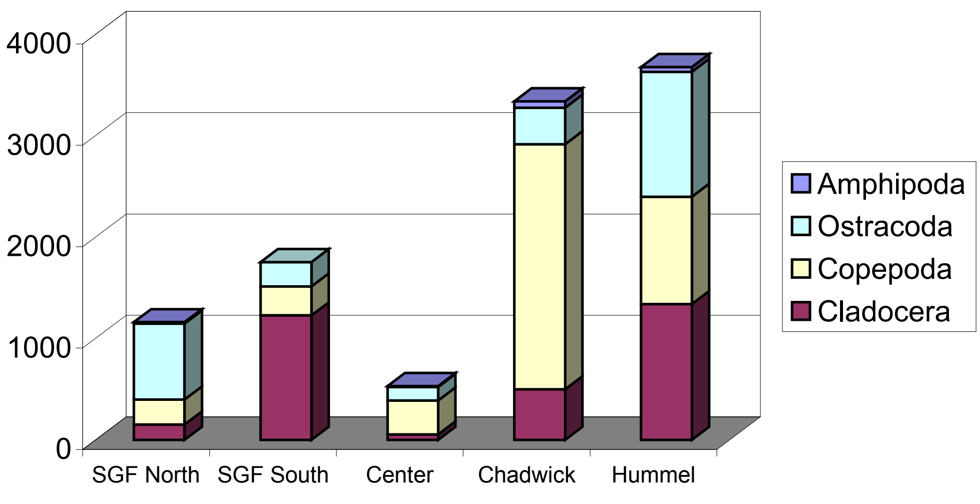
2. **Aquatic invertebrates**

In 2009, plankton tow collections were made at primary study sites until standing water was too shallow or ropey with decomposing algae, and at "blitz" sites that retained standing water in late August. As the summer progressed, increasing algal biomass made it more difficult to separate animals from the algae at the laboratory, and animal numbers may be less reliable as a result. Most field collections were "split" at least once to reduce and dilute algal mass for better visibility, or to make it easier to count very large numbers of animals. This procedure may also affect reliability of results, especially for the larger and scarcer animals that may come out in some splits but not others. To account for this, we frequently counted and compared two splits from the same tow.

Larval insects tend to be associated with aquatic plants and substrates, moreover, and are more amenable to collection with a kick-net than floating plankton net. While we did recover a significant number of aquatic larvae by kick-net, we were not satisfied with the quantitative reproducibility of this method, and only report larval aquatic insects here for limited purposes.

Our analysis here accordingly focuses on the more widespread, common aquatic crustaceans that may reliably provide quantitative indicators of wetland productivity and functioning. Planktonic crustaceans were observed on the first day of fieldwork in April 2009, and increased rapidly in June and July, after which we were no longer able to tow most of our study sites. Figure 10 shows mean crustaceans collected per tow for April to July 2009. Davis Farm is excluded because standing fresh water could only be found one time, and the entire site was influenced by residual salt water, making it non-comparable.

Figure 10: Mean crustaceans per tow
2009 season



Copepods were nearly all Calanoids, Cyclopoids comprising barely 2 percent of the total. Amphipods were exclusively Gammarid. Data in Figure 10 appear the reverse of relationships between sites in Figures 4 through 9, with crustacean abundance greatest at Hummel and Chadwick, the relatively least disturbed of our primary study sites. The diversity of crustaceans at these sites was similar, but evenness was greatest at Hummel. Dominance of Copepods at Chadwick and Center, Cladocera (Daphnids) at Sweet Grass Farm south, and Ostracods at the north unit of Sweet Grass Farm, is not easily explained. Daphnids are sensitive to water quality, and for this reason are used as a model organism in aquatic toxicology, yet they dominated one of our intensely managed farm sites. One important confounding factor is the depth and seasonal duration of standing water at our study sites. There was little standing water at Sweet Grass Farm by July, mostly shallow and quite warm, which was also true of Center pond by mid-July, whereas Chadwick and Hummel retained shaded deeper water throughout the summer. The relationship between sites shown in Figure 10 may be an artifact of wetland type and depth.

Abundance and diversity of insects should be less determined by these factors and (as suggested by the terrestrial data shown below) may therefore be a better standard for comparing the functioning of seasonal and perennial wetlands.

Mollusks were collected in a number of plankton tow and kick-net samples. Tiny freshwater fingernail clams (Sphaeridae) were found at Sweet Grass Farm, Chadwick and Center pond. They can be useful for monitoring toxic loading of wetland food webs from road runoff (Barsh et al. 2009). Small freshwater snails (Physidae) were also collected at Sweet Grass Farm and Center pond.

Few sites retained substantial standing water by the time of our “blitz” in August 2009. Crustaceans were recovered from the Center Road, Crossroads, Whiskey Hill, and Shoal Bay ponds, but no more than 65 total individuals (all species) from any one site.

3. Terrestrial invertebrates: the 2009 season

Common terrestrial invertebrates include Arachnida (spiders, mites, harvestmen), Myriapoda (millipedes, centipedes) and Insecta. As described under Methods, pan traps collected more diverse invertebrates than deadfall traps, but underrepresented Arachnida and Myriapoda. The following figures are restricted to insects, for comparability of data from 2009, when both deadfalls and pans were used, and 2010, taken solely from a larger number of pans at each site. Since somewhat different methods were employed each year we present and discuss the data from each year separately, before combining both years.

The abundance and diversity of insects at our study sites admits of many different levels of analysis. Total insect biomass and the diversity of insects (measured as number of orders, families, genera, or species) reflect the availability of nutrients, the complexity of habitats, and habitat quality (including absence of toxic contaminants). Reorganizing the data by guilds (groupings of species that have similar livelihoods) reflects the overall nature and structure of food webs. Evenness is a measure of balance amongst guilds, and is arguably a predictor of ecosystem stability or resilience.

Figures 11 and 12 compare primary study sites with respect to the total abundance and diversity in 2009. Insects were significantly more abundant at Sweet Grass Farm and the horse ranch at Center Farm in 2009. Diversity was comparable at all of the sites, however. In brief, then, SGF and Center produced more insect biomass with no sacrifice of insect diversity, when compared with a long abandoned farm (Chadwick), a grazed salt marsh (Davis), and a largely unfarmed freshwater marsh.

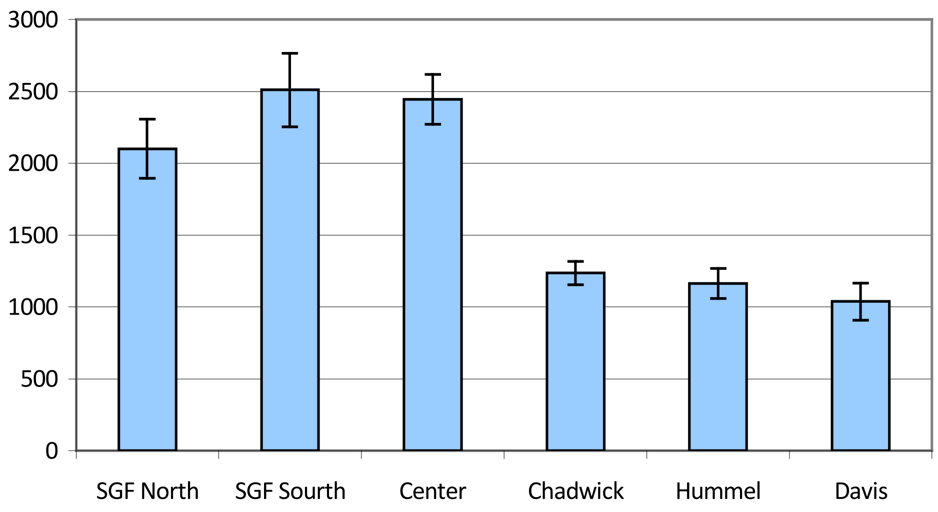


Figure 11: Total insects by site, 2009

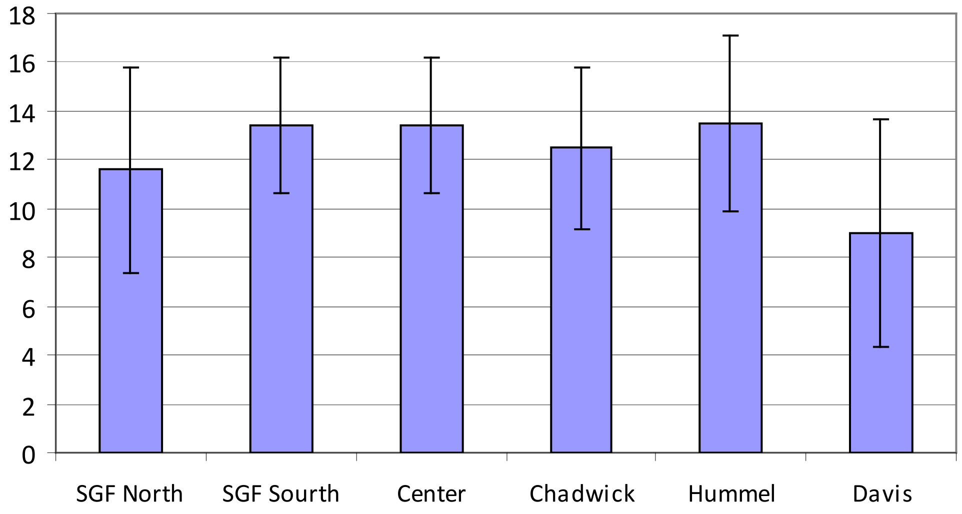
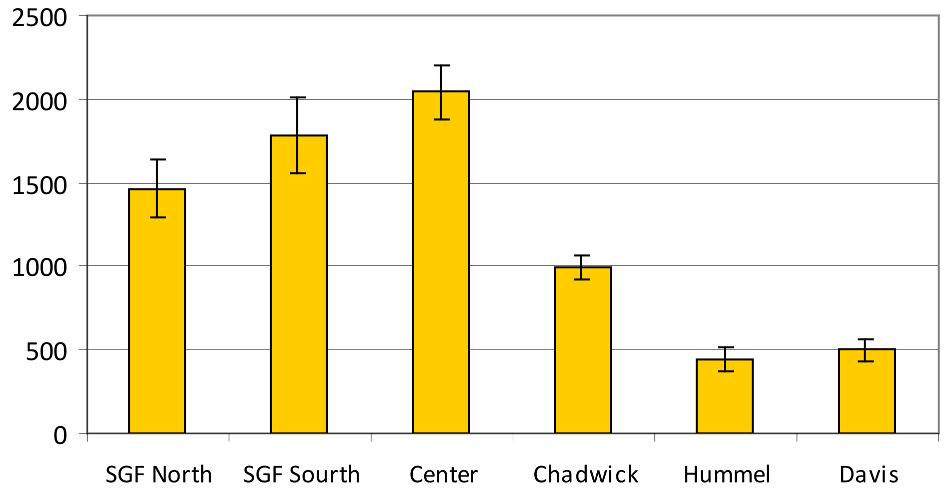


Figure 12: Insect Orders by site, 2009

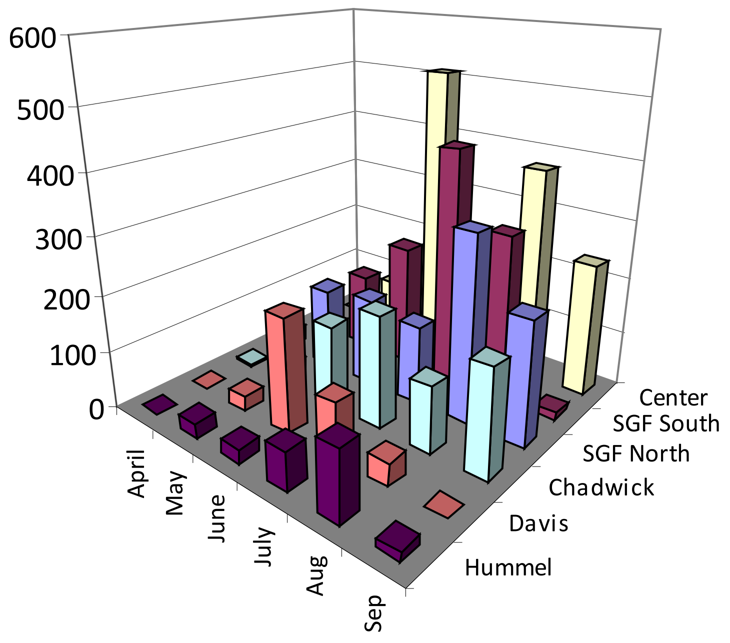
As shown in Figure 13, the main component of the difference in insect abundance between sites is the Diptera, which include many wetland fliers such as flies, mosquitoes, midges and crane flies that provide prey for local bats (chiefly the small mouse-eared bats *Myotis spp*) and birds such as swallows, bluebirds, and native sparrows.

Figure 13: Diptera by site, 2009

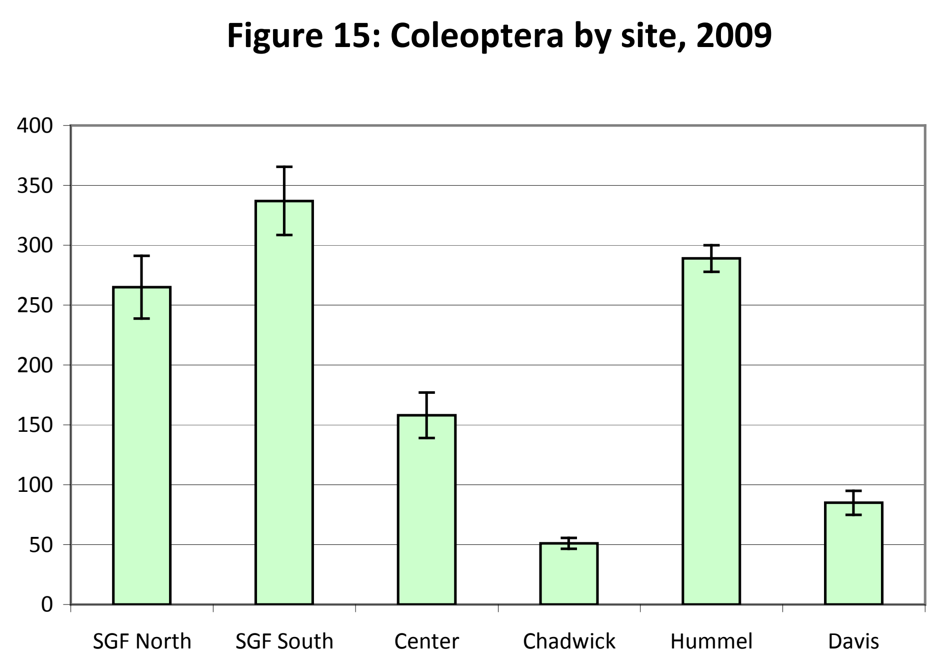


Diptera attained peak abundance earliest at Davis and Center Farm, later at SGF South and Chadwick, and only in late summer at SGF North and Hummel (Figure 14), a pattern that suggests a combination of biotic and anthropogenic (land use) factors.

Figure 14: Diptera by site, monthly, 2009



Diptera include many generalists, and thrive in disturbed, anthropogenic habitats such as homes, gardens, and fields. Their abundance may not be the most valid measure of habitat integrity. Coleoptera (beetles) are generally regarded as more specialized and a better indicator of habitat integrity and complexity. Coleoptera were relatively scarce at all of our study sites, compared to the Diptera. Their numbers were greatest at SGF, and at Hummel, our least disturbed site (Figure 15). This result suggests that disturbance is not the only factor explaining the relatively high total biomass of insects at SGF. At the same time, it appears that the high insect biomass at Center Farm ranch is largely due to disturbance, because it is accompanied by relatively few Coleoptera.



Arachnida are mainly predators, and as such they require a significant variety and abundance of prey to thrive. Arachnid abundance should therefore be correlated with the total biomass of insects, and may also reflect some of the components of insect diversity. As shown in Figure 16, arachnid abundance was relatively high at SGF and Center Farm (compare Figure 11) and also at Hummel (compare Figure 15). Once again SGF behaves in some respects like another intensively grazed farm (Center), but also like an unfarmed, relatively undisturbed parcel (Hummel).

In August 2009 we collected insect data from seven additional sites on Lopez that included both residential ponds and farm ponds, ranging in age from two to more than 20 years (Figure 17). Only one—Port Stanley, a salt marsh grazed only by wild geese—was comparable to SGF or to Center Farm in terms of insect abundance. Insect diversity was relatively low at this site, however (Figure 18). Diversity was comparable between SGF, Center Farm, Hummel, and many of the farmed wetlands and ponds. Reasons for the low diversity at some of the secondary study sites and not others remain unclear.

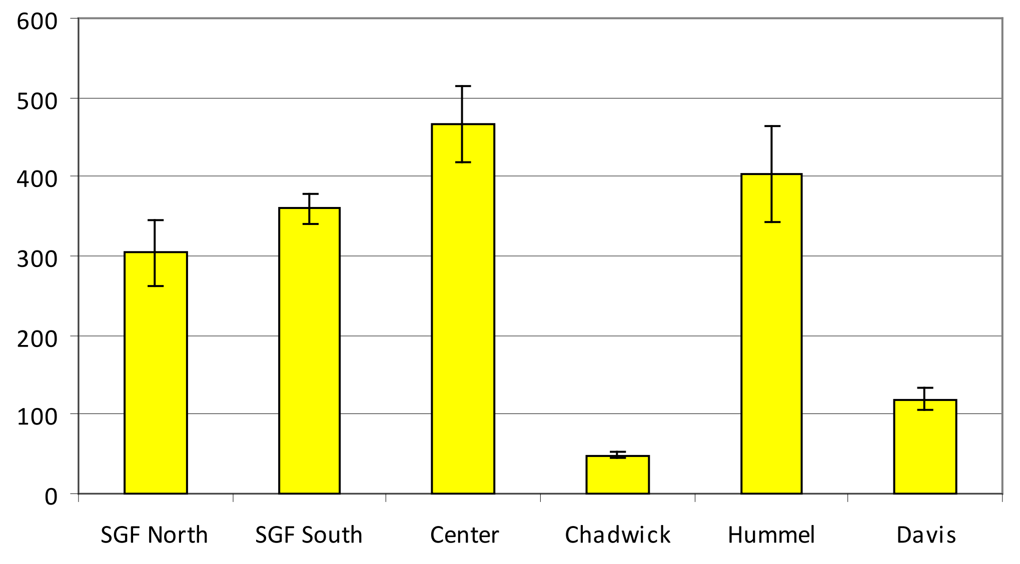


Figure 16: Arachnida by site, 2009

Diptera and Coleoptera comprised 80 percent of all insects collected in 2009. No other order accounted for more than five percent of our 2009 collection. Comparisons of sites with respect to poorly represented orders would be less reliable, and are not shown here. It is worth noting that Collembola (springtails) were considerably more abundant at Hummel than at any other site. These tiny detritivores are associated with terrestrial and aquatic leaf litter. Hummel was notable for the lowest dissolved nutrients of any primary site, and presumably has the largest share of its nutrients tied up in detritus.

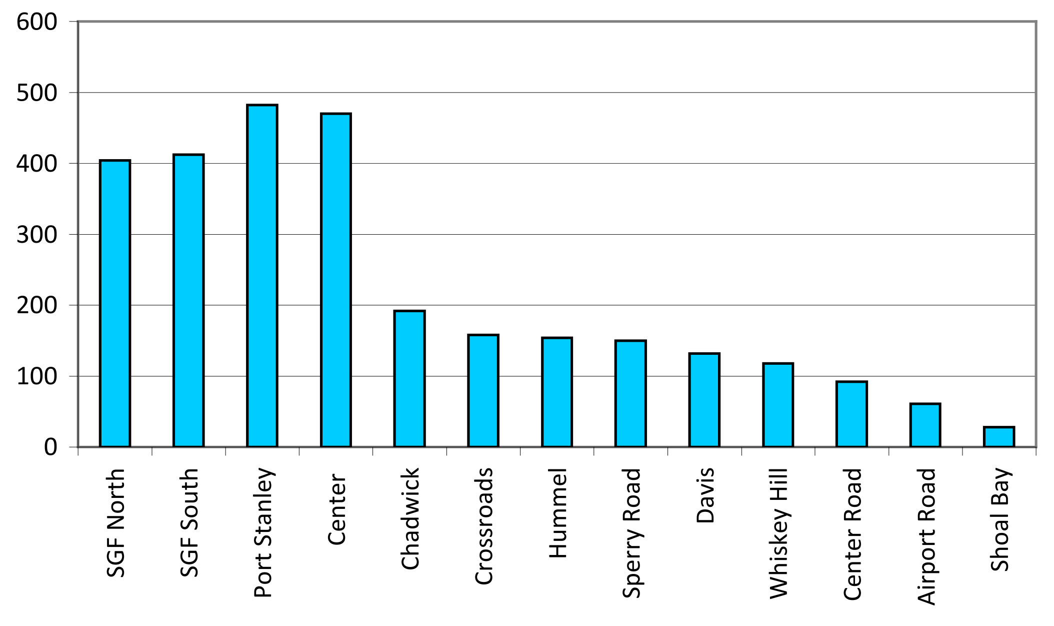
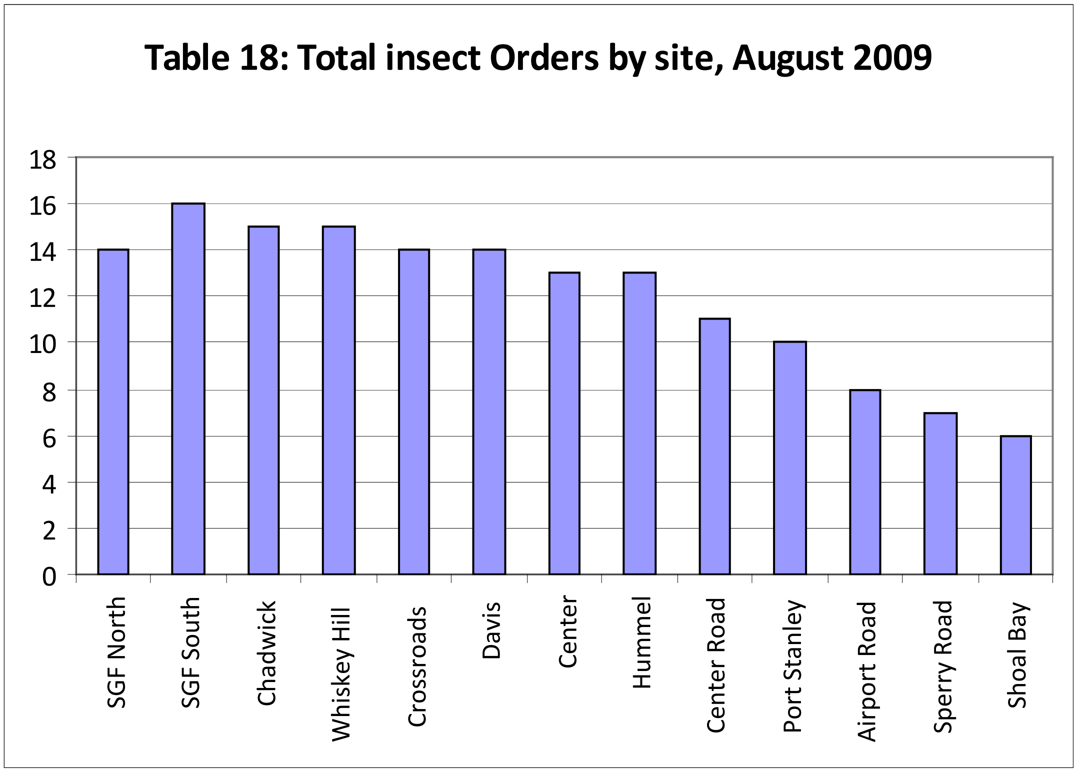


Figure 17: Total insects by site, August 2009



4. Terrestrial invertebrates: the 2010 season

At the outset, it should be noted that the Davis Farm site was abandoned in 2010, due to the fact that it was flooded with salt water in the wake of a tide gate failure, and as such the site is no longer meaningfully comparable to other sites on the island.

As noted under Methods, we abandoned deadfall traps in 2010 and increased the number of pan traps deployed at each site from five to 10 to improve reliability. Results from 2010 and 2009 are not strictly comparable, as a result; we cannot say with certainty that differences between the patterns observed in these two years were real or artifacts of the change in methods. At the same time, the change effected in 2010 resulted in a larger and probably more representative collection of insects, permitting us to explore patterns of abundance and diversity at a finer scale, *i.e.* at the level of insect Families. In addition, we felt confident in examining guilds and the structure of food webs, and in calculating indices of richness and evenness to compare our study sites at a structural level.

Reliability was also increased by more than doubling the frequency of sampling at each site, from monthly (spring) or bimonthly (summer) to weekly for the study season. At the same time, sampling was restricted to June, July and August, when insect numbers and diversity had been greatest at all primary study sites in 2009. As a whole, then, 2010 data is a better, more accurate picture of a smaller seasonal window in time.

Total insect abundance differed less dramatically in 2010 than 2009 (Figure 19). This may reflect different seasonal weather conditions and, at least as SGF and Center, different range management practices. Nevertheless, SGF South was the most productive site studied in 2010, as it had been in 2009.

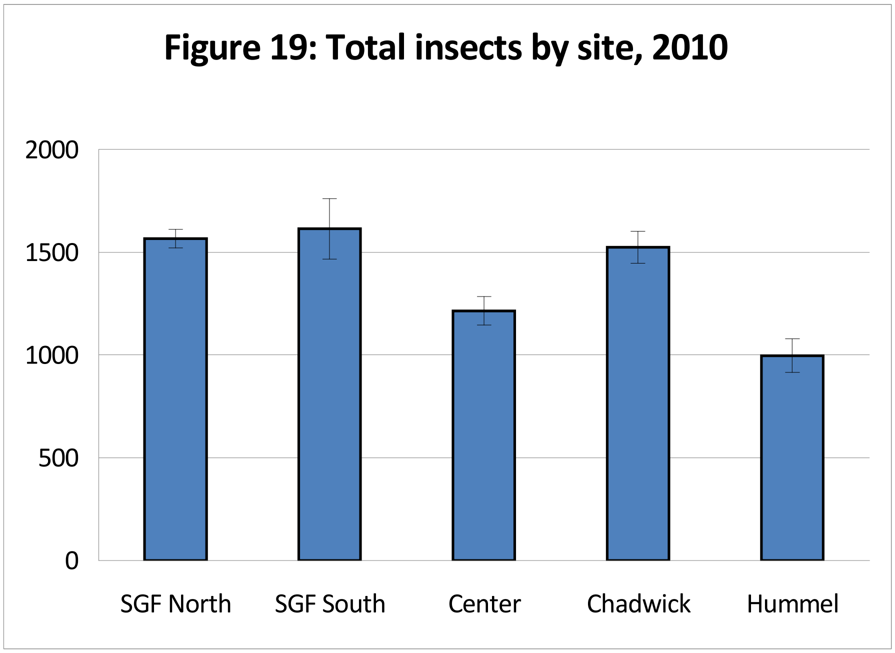


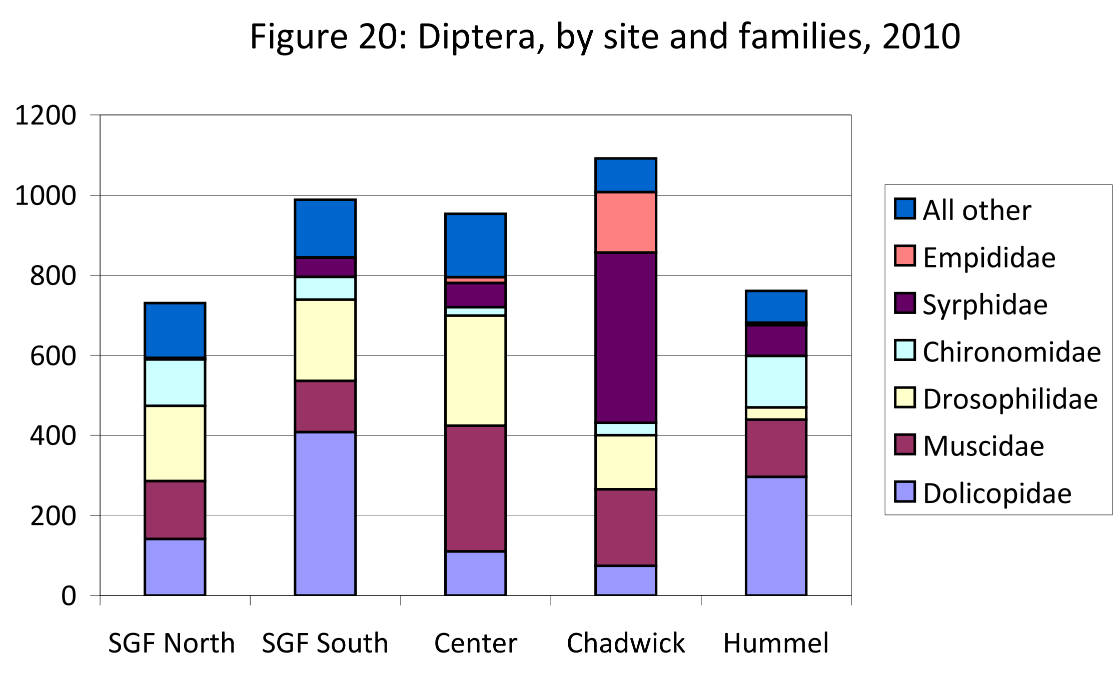
Figure 19: Total insects by site, 2010

Diptera continued to be the best represented insect order, albeit only three-fifths of the total insect collection in 2010 compared to nearly four-fifths of the total in 2009. Diptera were significantly more abundant at SGF (North and South) and Center in 2009 (Figure 13), but almost equally abundant at SGF, Center, and Chadwick in 2010 (Figure 20). Our abandonment of deadfall traps in 2010 should have increased the proportion of Diptera in the sample; hence the difference between 2010 and 2009 collections are likely to be due to other factors such as weather that affected all of our study sites.

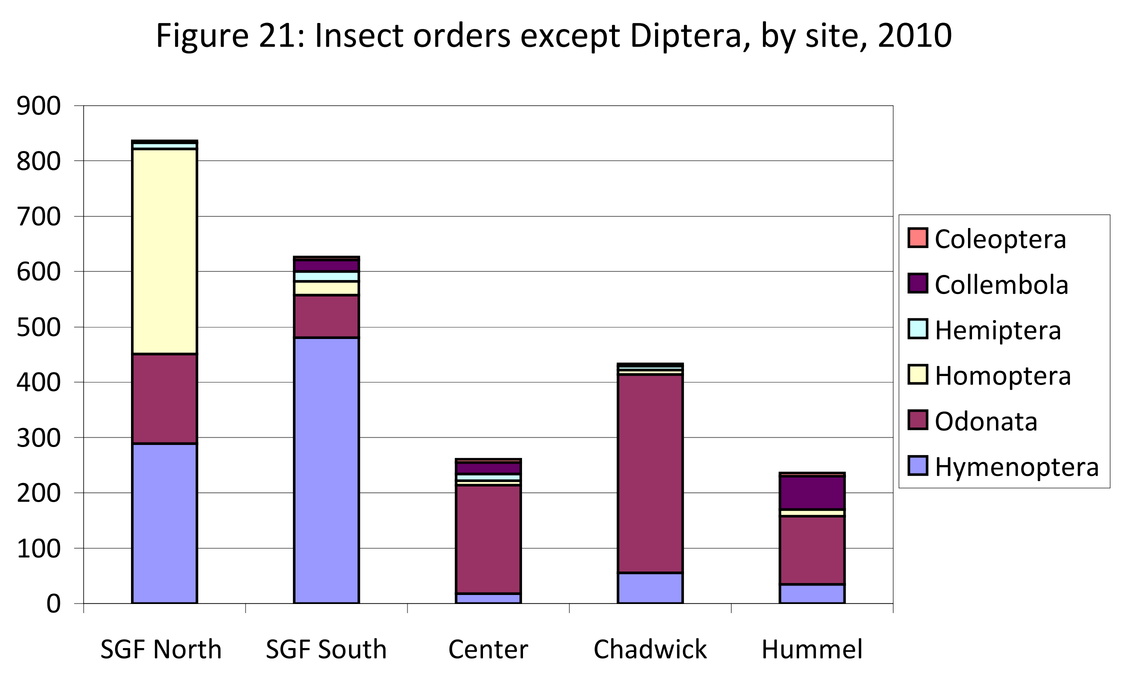
Family-level analysis of the Diptera data in Figure 20 suggests significant habitat differences between sites. Dolicopidae (long-legged flies) were the largest family at SGF South and Hummel: one of the most intensively grazed study sites, and the least disturbed study site. Syrphidae (flower flies) were dominant at Chadwick and the Muscidae (house flies) were most abundant at Center. Chironomidae (midges) were relatively abundant at SGF (North and South) and Hummel, but scarce at Center and Chadwick. Drosophilidae (fruit flies) were abundant everywhere *except* Hummel, while Empididae were significant *only* at Chadwick. No two sites shared quite the same pattern.

SGF shared similarities with Center in some respects, however, and with Hummel in others, as was also seen in 2009. It may not be inaccurate to describe SGF (North and South) as intermediate between Center, a comparably heavily grazed site, and Hummel, a relatively undisturbed site

Other than the Diptera, insects were not particularly diverse at the family level in 2010. The Coleoptera were overwhelmingly predatory ground beetles belonging to the Carabidae and Staphylinidae. The Hemiptera were almost entirely Saldidae; Homoptera were nearly all Aphididae; and the Hymenoptera chiefly small parasitoid species such as Ichneumonidae although some Apidae, Formicidae, and Vespidae were also collected.



As a whole, study sites differed significantly at the level of insect orders, however (Figure 21).



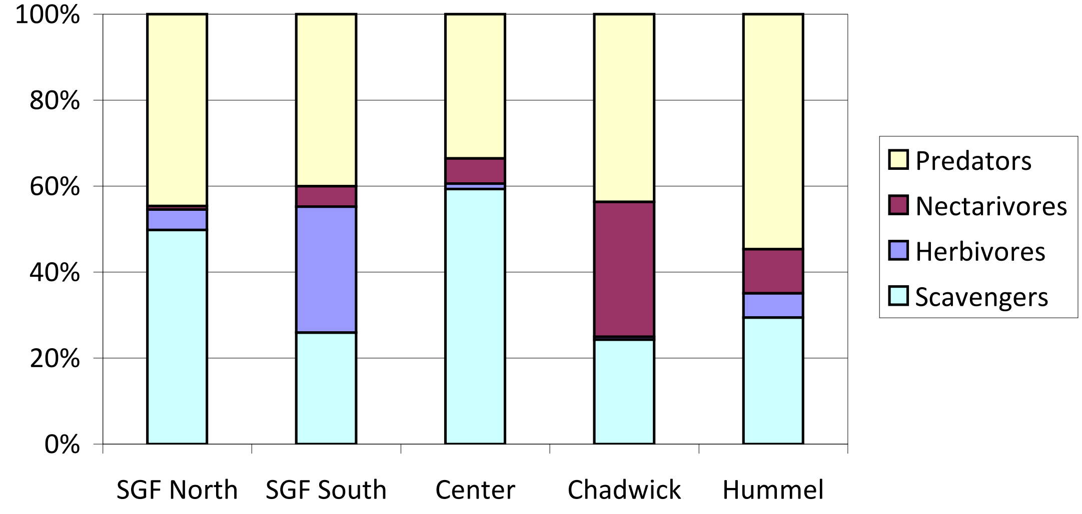
Like Figure 11, Figure 21 suggests higher productivity at SGF (North and South) than at other farmed and unfarmed sites. SGF is distinguished from other study sites by the abundance of Hymenoptera and (at SGF North) the abundance of Homoptera. Recall that most of the Hymenoptera were parasitoids, and most of the Homoptera were aphids. Parasitoids are highly specialized, and can serve as an index of overall insect diversity at the genus and species levels. Aphids, by comparison, are grazers at the bottom of insect food webs, benefiting from fresh plant growth.

The prevalence of Odonata (dragonflies and damselflies) at our other study sites is probably due, at least in part, to the persistence of large patches of open water at those sites. At SGF, plant growth fills the shallow central wetland by midsummer, rendering it less attractive for Odonata to continue to lay eggs and rear as nymphs into August. Hence at SGF, it would appear that wasps fill the role filled at other study sites by Odonata.

Collembola were most abundant at Hummel in 2010, as they had been in 2009, an indicator of detrital accumulation in Hummel Lake and surrounding marshes.

Reorganizing the 2010 data by guilds confirms structural differences in food webs amongst our study sites (Figure 22). The large proportion of herbivores at SGF South (chiefly aphids) is consistent with vigorous plant growth. Nectarivores were conspicuous at Chadwick, presumably due to the large proportion of flowering shrubs and trees at that site (Appendix A).

Figure 22: Insect guilds by site, 2010



Notwithstanding the differences that appear in Figures 20, 21, and 22, our study sites were comparable in terms of richness (number of insect families) and the Shannon index of evenness (Figures 23 and 24). At least with respect to insects, farmed sites were not significantly degraded in comparison with abandoned farms or relatively undisturbed sites.

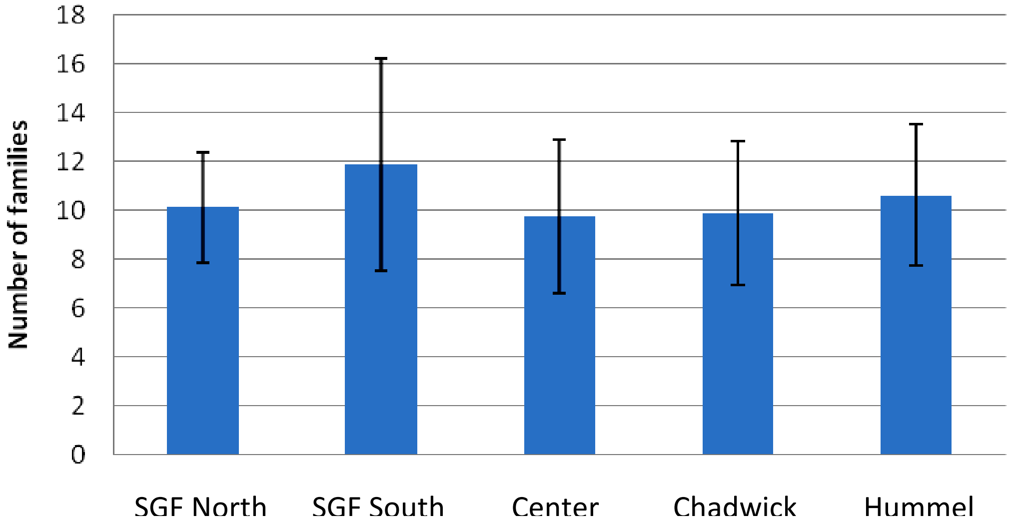


Figure 23: Richness of insect families, 2010

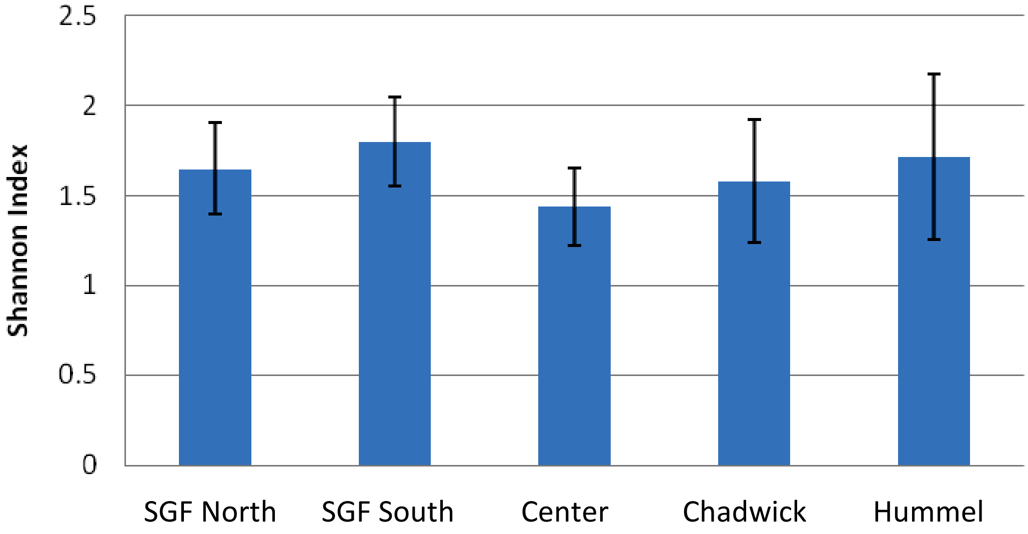


Figure 24: Evenness of insect food webs, 2010

Discussion

Two major questions initiated this study: How much do farming methods matter? Can well-managed wetland farms be comparable to unfarmed wetlands land with regard to the productivity and diversity of native wetland fauna? A practical corollary question also arose. What is the best way to measure and monitor agricultural impacts on wetland ecosystems in the San Juan Islands?

Answers to these questions have immediate applications to local decision-making. If the choice of land management practices can bring existing wetland farms to a par with abandoned wetland farms, it is more reasonable to improve farming practices than to seek to reduce or eliminate wetland farming. The practices at Sweet Grass Farm, if validated, can serve as a template for other agricultural operations in the islands.

The threshold consideration is adoption of a standard for comparison of wetlands, farmed and unfarmed (relict "natural" areas or abandoned farms). We have relied chiefly on two kinds of quantitative indicators: nutrient cycling, and invertebrate diversity. Over the course of this two-year study, we refined our methodology with a view to economy as well as underlying validity and reliability, and in the hope that an economical and reliable assessment framework would encourage farmers and their community to monitor farming impacts on a continuing basis.

Aquatic invertebrates proved difficult to collect in mid- to late summer when most wetlands shrink and grow dense algal mats. Aquatic insect larvae, being largely benthic, were especially challenging to collect quantitatively. Terrestrial invertebrates were much easier to collect systematically, using deadfall traps and pan traps. Pans provided the best results (number and diversity of insects collected). We deployed five pans at each site in 2009 and 10 per site in 2010. The principal advantage of using a larger number of pans was lower risk of losing most or all of a sample to overturned pans. The number of pans deployed at each study site had a negligible effect on family-diversity results (Figure 25), and only a small positive effect on catch-per-unit-of-effort (Figure 26).

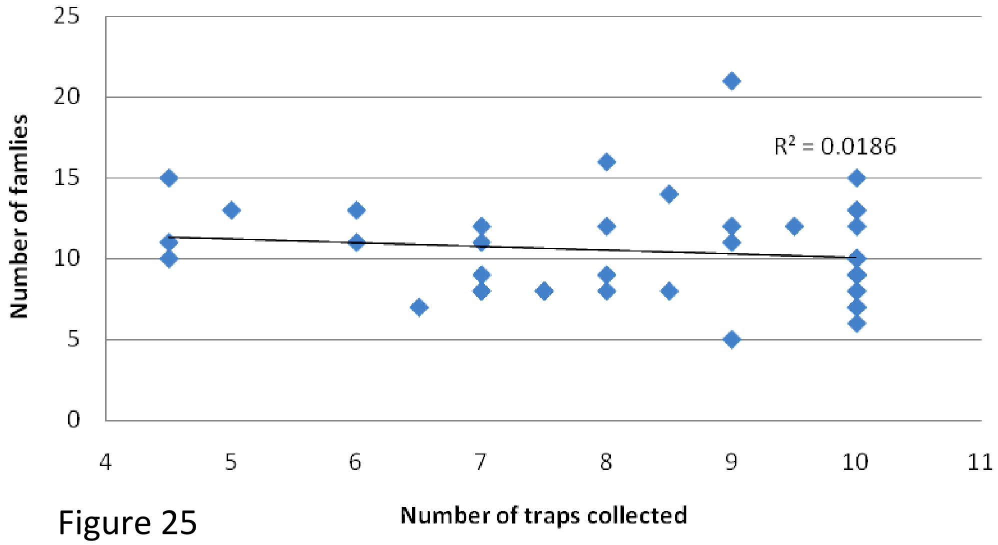


Figure 25

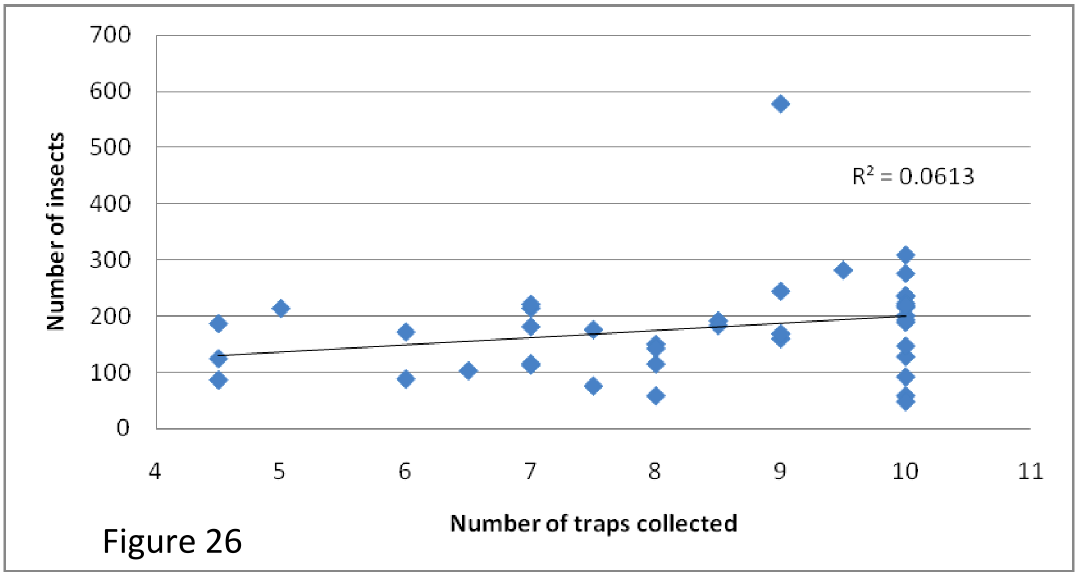


Figure 26

Insect biomass and diversity are often used as food web indicators in experimental ecology (*e.g.* Scherber et al. 2010). Insects are numerous and easy to collect compared to birds, fish and small mammals. Although protecting vertebrates may be the real concern, trapping and counting insects provides greater statistical power in less time and at lower cost than tracking larger animals. In the present study, insect collections did discriminate between our study sites in ways that could be reasonably interpreted.

Differences in weather between the 2009 and 2010 study seasons may explain a great deal of the differences observed in relative insect biomass between sites (Figures 11 and 21). From May through June 2009 the weather was unusually dry; this was followed by a record heat wave in July 2009. By contrast, in 2010 a warm winter was followed by unusually cool, wet May and June weather. Summer 2010 was relatively cool, broken by brief heat waves in July and August. Conditions favored early insect emergence in 2009. Insect survival should have been high over the 2009-2010 winter, but conditions for their emergence were poor until July. Long-lived insects such as predatory ground beetles and dragonflies (which can remain as nymphs underwater for a year or longer) enjoyed some advantage from the delayed heat in 2010; short-lived Dipterans were disadvantaged.

Sweet Grass Farm produced more Diptera than other study sites in 2009 and more non-Diptera in 2010. It was highly productive for insects both years, but not for the same insect orders, and not to the same extent. This observation has important implications for climate change. If the islands experience cooler, wetter conditions on the whole, we may see more summers with invertebrate patterns like 2010.

Management practices probably also affected our results. Less wetland area was grazed or mown in 2010 at Sweet Grass Farm, in part because of greater water retention: water levels were unusually high and wetland edges were impassable. Management was unchanged at the comparison sites. To the extent that disturbance is facultative for insect populations, the fact that Sweet Grass Farm was less extensively disturbed in 2010 is one possible explanation for its relatively poor performance in 2010.

Conclusions

In brief, our data show that:

1. Pasture management practices at Sweet Grass Farm liberate significantly more dissolved nutrients (nitrogen, phosphorus, and carbon) than we observed in other grazed, formerly grazed and relatively undisturbed wetlands and ponds on Lopez Island.

2. Insect abundance and diversity at Sweet Grass Farm were equal to, or exceeded what we observed in other Lopez wetlands, whether farmed or unfarmed. Differences in results between 2009 and 2010 can largely be attributed to differences in weather, as well as different patterns of mowing and rotational grazing at Sweet Grass Farm.

3. Insect biomass and diversity were not sacrificed for high levels of quality beef production at Sweet Grass Farm. Species composition differed between grazed wetlands, including Sweet Grass Farm, and the formerly grazed and relatively undisturbed wetlands included in this study—for example with respect to the prevalence of detritivores.

These results are consistent with the findings of a number of recent studies of the impacts of agriculture on insect communities and, by extension, on wider food webs that include sensitive vertebrate species (Crowder et al. 2010; Gabriel et al. 2010; Hodgson et al. 2010). Food production systems do not necessarily degrade invertebrate communities although they alter species composition. Likewise, cessation of food production does not necessarily result in the regeneration of "natural" pre-agricultural invertebrate food webs. Rather, abandonment may result in reduced invertebrate biomass and diversity.

The implication of this study is not to encourage converting relatively undisturbed wetlands to farms. The potential for loss of *particular* species remains whenever the use of land changes, and this effect may be irreversible if farming is subsequently abandoned. On the other hand, converting existing farms and ranches to unfarmed preserves will not, at least under the conditions prevailing in the San Juan Islands, result in richer, more even or more productive invertebrate food webs.

Acknowledgments

This project was made possible by a *Pioneers in Conservation* grant from the National Fish and Wildlife Foundation; by students that assisted in field collections and analyses (Lyra Dalton, Makenna Henriksen, Will Jacobson, Emily McLeod, and Tamira Vojnar); and by the landowners that gave our team access to their wetlands and ponds.

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Appendix A

Plant communities of study sites

			SGF-N	SGF-S	Center	Chadwick	Hummel	Davis
Ferns & Allies	Field horsetail	*Equisetum arvense*			X	X		
	Purple-fringed riccia	*Ricciocarpos natans*					X	
Trees Shrubs	Snowberry	*Symphoricarpos albus*				X		
	Pacific crabapple	*Malus fusca*				X		
	Nootka rose	*Rosa nutkana*				X		
	Himalaya blackberry*	*Rubus armaenicus*				X		X
	Trailing blackberry	*Rubus ursinus*						X
	Hardhack	*Spirea douglasii*				X	X	
	Scouler's willow	*Salix scoulerii*				X		
	Hooker's willow	*Salix hookeriana*					X	
	Bittersweet nightshade*	*Solanum dulcamara*					X	
Forbs	Canada thistle*	*Cirsium arvense*	X			X		
	Bull thistle*	*Cirsium vulgare*	X					X
	Brass buttons*	*Cotula coronopifolia*						X
	Marsh cudweed	Gnaphalium palustre	X					
	Chamomile*	*Matricaria chamomilla*	X					
	Hairy cat's-ear*	*Hypochaeris radicata*	X					X
	Shasta daisy*	*Leucanthemum maximum*						X
	Dandelion*	*Taraxacum officinale*		X				X
	Chicory*	*Cichorium intybus*		X				

			SGF-N	SGF-S	Center	Chadwick	Hummel	Davis
	Mouse-ear chickweed	*Cerastium fontanum*	X					
	Skullcap speedwell	*Veronica scutellata*	X	X				
	Sandspurry	*Spergularia sp*						X
	Common orache	*Atriplex patula*						X
	Red goosefoot*	*Chenopodium rubrum*						X
	Sea asparagus	*Salicornia virginica*						X
	Bird’s-foot trefoil*	*Lotus pedunculatus*	X					X
	Red clover*	*Trifolium pratense*						X
	White clover*	*Trifolium repens*	X					X
	American vetch	*Vicus Americana*						X
	Willowherb	*Epilobium cillatum*						X
	Narrow-leaved plantain*	*Plantago lanceolata*						X
	Broad-leaved plantain*	*Plantago major*	X					X
	Curly dock*	*Rumex crispus*	X	X				X
	Doorweed*	*Polygonum aviculare*	X					
	Water smartweed	*Persicaria amphibium*	X					
	Pond mint	*Mentha arvensis*				X		
	Creeping buttercup	*Ranunculus repens*	X			X		
	Celery-leaved buttercup	*Ranunculus sceleratus*						X
	Pacific cinquefoil	*Potentilla anserina*	X	X		X		**X**
	Small bedstraw	*Galium trifidum*	X			X		
Sedges Rushes	Slough sedge	*Carex obnupta*				**X**		
	Inlated sedge	*Carex urticulata*			X			

			SGF-N	SGF-S	Center	Chadwick	Hummel	Davis
	Marsh spikerush	*Eleocharis palustris*				X		
	Creeping spike-rush	*Eleocharis palustris*			X			X
	Soft rush	*Juncus effuses*	X	X	X	X		X
	Woodrush	*Luzula multiflora*						X
	Burreed	*Sparganum emersum*						X
Grasses	Canary reedgrass*	*Phalaris arundinacea*	**X**	**X**	**X**	**X**	**X**	**X**
	Water foxtail	*Aleopecurus geniculatus*	X	X				X
	Velvet grass*	*Holcus lanatus*	X					
	Sweet vernal grass*	*Anthoxanthum odoratum*						X
	Orchard grass*	*Dactylis glomerata*						X
	Seashore saltgrass	*Distichlis spicata*						**X**
	Tall fescue*	*Lolium arundinaceae*						X
	Timothy*	*Phleum pratense*						X
	Seaside arrowgrass	*Triglochin maritimum*						X
Aquatics	Cattail	*Typha latifolia*			**X**		**X**	
	Common mare's-tail	*Hippuris vulgaris*				X		
	Small duckweed	*Lemna minor*		X	X			
	Large duckweed	*Spirodela polyrhiza*			X	X	X	
	Floating-leaved pondweed	*Potamogeton natans*		X		X		
	Yellow pond lily	*Nuphar lutea*			**X**			
	Common bladderwort	*Urtricularia macrorhiza*			X			