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This study at the University of Maryland had two primary goals. One of the overall goals of this project was to determine if surface waters adjacent to golf courses were contaminated by pesticides and/or fertilizers. In addition, since chemicals applied to golf courses have been shown to affect aquatic organisms, a second goal was to develop the use of stream macroinvertebrates and their communities as long-term indicators of water quality to identify possible chronic effects of golf course management practices.

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PURPOSE

The purpose of *USGA Turfgrass and Environmental Research Online* is to effectively communicate the results of research projects funded under USGA's Turfgrass and Environmental Research Program to all who can benefit from such knowledge. Since 1983, the USGA has funded more than 290 projects at a cost of $25 million. The private, non-profit research program provides funding opportunities to university faculty interested in working on environmental and turf management problems affecting golf courses. The outstanding playing conditions of today's golf courses are a direct result of ***using science to benefit golf***.

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Pesticide and Fertilizer Contamination of Streams Adjacent to Golf Courses and the Response of the Benthic Macroinvertebrate Community

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SUMMARY

High-quality golf courses require substantial pesticide and fertilizer applications, leading to concerns about their environmental impacts. A study was conducted the effects of golf course pesticides and fertilizers on adjacent surface waters and the their impact on benthic macroinvertebrates.

- Stream water and benthic macroinvertebrate community samples were collected from mid-Atlantic golf courses; samples were collected from sites upstream and downstream of the courses for comparison. Water samples were collected following runoff events (for pesticide and nutrient analysis) and on a monthly basis (for nutrient analysis).
- Macroinvertebrate communities were analyzed using bio-assessment indices. While increases in abundance and taxa richness of invertebrates downstream of the courses were seen, no significant shifts in community structure and function between sites were found.
- Higher downstream concentrations of several pesticides and phosphorus in runoff samples indicated contamination by these chemicals. However, monthly sampling did not reveal increases in downstream nutrient concentrations. Therefore, fertilizer applications do not appear to contribute to long-term stream nutrient enrichment.
- Golf course management practices did not appear to impact stream-macroinvertebrate communities. However, since the potential for problems exists further downstream (e.g. in the Chesapeake Bay), studies on turfgrass management practices that minimize potential chemical movement, such as riparian vegetation maintenance, are justified.

Golf courses are viewed as an ecologically sound use of land that provide citizens with a convenient recreational opportunity while preserving green space and natural settings (39). Yet, in order to keep the grounds appealing and provide high-quality playing conditions, the use of pesticides and fertilizers on golf courses is an inherent necessity. The treatment of a golf course with these chemicals is usually highly visible. As a result, public concern over the possible environmental harm associated with the use of pesticides and fertilizers on golf courses has increased in recent years (25, 39), in spite of increased regulation and enhanced turf and pest management practices (22, 28).

Citizens that live near golf courses are often particularly concerned about whether or not these chemicals are entering ground water they drink or surface waters used for recreational activities, such as fishing and swimming. Therefore, golf course superintendents need to know if their pesticides and/or fertilizers are entering local water systems and whether their management practices are having beneficial or detrimental effects on the environment. In response to these concerns, we completed a project that studied the runoff of pesticides and fertilizers into surface waters that flow through golf courses and the impact of these chemicals on benthic macroinvertebrates and their communities.

The pesticides and fertilizers commonly applied to turfgrass systems face various fates including volatilization, leaching, and runoff. With respect to the water quality, the fates of most

With respect to water quality on and around golf courses, leaching and runoff are the fates of primary concern.

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concern are leaching and runoff. The movement of pesticides and nutrients into aquatic systems is of interest because of the possible non-target effects these chemicals may have. Therefore, numerous studies have been completed focusing on the transport of pesticides and nutrients from turfgrass into aquatic systems.

Watschke et al. (39) studied the movement of pesticides and fertilizers applied to golf courses. They concluded that "dense, high-quality turfgrass stands, regardless of establishment method, affect the overland flow process to such a degree that runoff is insignificant." In addition, Kenna (17) stated "results...often show that turfgrass systems reduce runoff" which "reinforce(s) the view that turfgrass areas generally rank second only to undisturbed forests in their abiility to prevent pesticides from reaching ground water and surface water." Similar conclusions were also reached by Miles et al. (23) and Gross et al. (8).

However, other authors have found movement of pesticides and nutrients from turfgrass systems into surface water via runoff. For instance, Hong and Smith (15) reported detecting dithiopyr in runoff water from treated simulated golf course fairways. Also, Sudo and Kunimatsu (37) found pesticide loading of a stream associated with a golf course in the Shiga Prefecture of Japan. Smith (35) found that 8% of applied pesticides moved out of a turf system via runoff over a 25-day sampling period following the treatment of simulated fairways; runoff was the result of both simulated and natural rain events. The data lead Smith to conclude "that there is a need for additional improvement of the management strategies used on fairways to decrease the amount of pesticides leaving these areas during a rainstorm following application."

Finally, Morton et al. (26) studied the influence of fertilization and over watering on the loss of nitrogen from home lawns. While they determined that runoff from turfgrass was not a significant source of inorganic nitrogen loss, over watering in conjunction with fertilization generated significantly greater leaching of nitrogen. Indeed, they concluded that overwatering of fertilized lawns in coastal watersheds can result in increased nitrogen loading, thus threatening the health of bays and estuaries. The movement of pesticides and nutrients in tosurface waters can lead to a degradation of water quality, resulting in deleterious impacts on aquatic organisms, including benthic macroinvertebrates.

The relationship between water quality and macroinvertebrates has been recognized for at least 150 years. In 1848, it was noticed that the disappearance of Trichoptera larvae could be caused by the presence of an upstream city (24). Since that time, biomonitoring has become a standard method of monitoring the health of aquatic ecosystems. Biological monitoring (or biomonitoring) is "the systematic use of living organisms or their responses to determine the quality of the environment" (33). Biomonitoring, as Matthews notes, can be used to evaluate changes in the environment with many changes being from anthropogenic sources (33). Biomonitoring can study aquatic organisms from an individual to a community basis (16).

On an individual basis, morphological and/or behavioral changes can indicate the presence of a stressor. Biological monitoring of aquatic communities can study numerous community structural and functional dynamics since aquatic organisms respond to stress in a variety of fashions. Various changes in the structure of a community, such as decreases in taxa richness, the number of individuals or taxa of sensitive organisms (e.g., mayflies, caddisflies, and stoneflies), diversity of taxa, or shifts in the species composition of the community can indicate decreasing water quality.

Biomonitoring is often used to study the impacts of agricultural practices on aquatic ecosystems. One such agricultural practice is the management of golf courses. Golf course managers commonly utilize a variety of management practices in order to maintain the coursesuch that they provide optimal playing conditions and are aesthetically pleasing (39). These practices can include modifications to the landscape and occasionally surface waters on the golf course property, as well as chemical applications to the golf course in order to control pests and promote a healthy turfgrass stand.

While modifications to the landscape have the potential to impact aquatic communities, the environmental impacts of chemical applications to golf courses is of perhaps the greatest concern. The application of large amounts of these chemicals has brought about questions concerning their fate and subsequent environmental impacts, including their potential impact on aquatic systems, especially since "the greatest potential environmental hazards of pesticides are probably to aquatic organisms" (41). As has been noted, several studies have verified that pesticides and fertilizers applied to agricultural (including turf) and urban systems have contaminated surface waters. Therefore, the nontarget impact of these chemicals on aquatic organisms has become a topic of concern.

Several authors have studied the impacts of pesticides and nutrients on aquatic ecosystems. For instance, Kersting and Van den Brink (18) found a decrease in primary production and oxygen consumption, as well as a decrease in decomposition of organic matter due to the death of arthropods, following exposure to Dursban® 4E (active ingredient, chlorpyrifos). In addition, they reference a study by Wallace who found a decrease in the abundance of insect shredders upon treatment of a stream by methoxychlor; the decrease in shredders resulted in decreased leaf processing rates. Cuppen et al. (5) treated microcosms with chlorpyrifos that resulted in a decrease in the number of shredders (*Gammarus pulex* was eliminated and the populations of *Asellus aquaticus* and *Proasellus meridianus* collapsed); the loss of shredders lead to a decrease in the decomposition of particulate organic matter.

The three primary concerns regarding nutrient enrichment of aquatic ecosystems are 1) eutrophication of surface waters, 2) contamination of drinking water by nitrogen (especially nitrate), and 3) of most recent concern in the Atlantic region of the United States of America- Pfiesteria outbreaks. Carpenter et al. (3) have identified many problems related to enrichment of aquatic systems including toxic algal blooms, oxygen depletion, fish kills, loss of biodiversity, and loss of aquatic plant beds and coral reefs.

While high levels of nutrient enrichment have shown to be problematic, moderate levels of nutrient enrichment of aquatic ecosystems have been found to result in increases in biological productivity, including increased abundance and/or biodiversity of aquatic organisms, of those systems. Brock et al. (1), upon the addition of nutrients to microcosms, saw increases in the abundance of macroinvertebrate grazers (the oligochaete *Stylaria lacustris* and several snail taxa). Rader and Richardson (30) studied the community composition of invertebrates and small fish in enriched and unenriched sections of the Florida Everglades. They found increases in species richness, Shannon's diversity, number of unique species, and density of organisms in enriched areas of the Everglades; however, the trophic structure and functional feeding-groups were similar at all sites along the nutrient gradient. Finally, in studies looking at the effects of nutrient additions on algae and periphyton, Winterbourn (42) found greater periphyton biomass on nitrogen and phosphorus enriched substrates and Niederhauser and Schanz (27) found higher algal biomass on clay pots containing phosphorus.

The studies we completed differed from many reported in the literature in several ways. First, most of the research that studied the movement of chemicals via runoff used artificially generated runoff events, whereas our studies focused on the movement of chemicals following natural storm events. In addition, not all of the studies focused on the movement of pesticides commonly applied in the mid-Atlantic region of the United States. Furthermore, most of the studies were completed in regions of the United States other than the mid-Atlantic region, if not in other parts of the world (e.g., Japan).

Whether or not pesticides contaminate surface waters is often a function of their half-lives, their ability to bind to organic matter in soils or other soil particles, their solubility in water, and the length of time between their application and an event (e.g., a major storm or irrigation) that results in runoff of water and soils from golf courses (17, 23). Since the Mid-Atlantic section

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of the United States has a unique climate and soil composition, the movement of pesticides and nutrients in this area may be different than the trends seen in other geographic regions in which similar studies have been completed. Finally, our research studied not only the movement of pesticides and fertilizers from golf courses into surface waters following natural runoff events, it also focused on the impact of golf course management practices on the benthic communities of these surface waters.

This study had two primary goals. One was to determine if surface waters adjacent to golf courses were contaminated by pesticides and/or fertilizers. Contamination was expected to occur especially in association with high runoff events such as storms (23, 35). In addition, since chemicals applied to golf courses have been shown to affect aquatic organisms, a second goal was to develop the use of stream macroinvertebrates and their communities as long-term indicators of water quality to identify possible chronic effects of golf course management practices.

One of the objectives of this study was to measure the concentration of pesticides in the water column of streams immediately following runoff events. Water samples were collected five times in 1998. Samples were processed and analyzed using solid phase extraction and gas chromatography/mass spectrometry to determine if pesticide contamination of streams adjacent to golf courses occurred during runoff events.

A second objective was to measure the concentration of nutrients (nitrate and phosphorus) in streams adjacent to golf courses. Stream water samples were collected once or twice a month in 1998 and 1999, as well as following the 5 runoff events mentioned above. The samples were analyzed for nitrate and total phosphorus content to determine if the application of fertilizers to golf courses was contributing to the enrichment of surface waters.

The third objective of this study was to assess the impact of golf course management practices on stream macroinvertebrate communities. Benthic macroinvertebrate communities of streams adjacent to golf courses were sampled 5 times in both 1997 and 1998 using artificial leafpack samplers. The benthic macroinvertebrates were sorted, counted, and identified. Benthic macroinvertebrate community structure (richness, diversity, etc.) was analyzed using several bioassessment indices to determine if benthic macroinvertebrate community composition at sites upstream from golf courses differs from that of sites downstream of golf courses.

In addition, since benthic macroinvertebrate communities are affected by factors other than the presence or impact of a pollutant, including natural physical and chemical parameters of water quality and habitat, several of these stream properties were measured in conjunction with benthic macroinvertebrate sampling. Therefore, if any differences were seen in the benthic macroinvertebrate communities when comparing upstream and downstream sites, it could be determined if these differences were due to natural variability of the physical and chemical properties of the stream instead of impacts of golf course management practices. Information gained from the analysis of the benthic macroinvertebrate community was used in conjunction with the results of the pesticide and nutrient studied to determine the impact of golf course management practices on aquatic communities.

In accordance with these three objectives, this study was completed to determine if pesticides and/or nutrients were contaminating surface waters, especially through runoff, and if they affected the macroinvertebrate community. If pesticides and fertilizers applied to golf courses were found to be contaminating streams adjacent to golf courses, this information could be used to explain any alterations in benthic community structure which may be seen at sites subjected to golf course runoff.

In addition, if it was found that pesticides and/or fertilizers adjacent to golf course management were not found in surface waters, or they were not impacting the benthic community, the controversy and negative image that now surrounds chemical use on golf courses may be reduced. Indeed, some management practices associated with golf courses (e.g., development and/or maintenance of a riparian zone) may actually allow the enhancement of stream water quality. Yet, if contaminants were present and/or were impacting the benthic community, this information could serve as the basis for the development of new, environmentally sound or alternative golf course management practices.

MATERIALS AND METHODS

Study Site Design

The study site design incorporated the use of four golf courses each year of the study. Courses 1, 2, and 3 were used in both 1997 and 1998 for benthic macroinvertebrate sampling. In addition, Course 4 was used in 1997 and Course 5 was used in 1998. All 5 courses were located along the Baltimore, Maryland/ Washington D.C. corridor. Courses 1, 2, and 3 were located in the Piedmont Province and Course 4 was located in the Coastal Plains Province; Course 5 was located along the border of the Piedmont and Coastal Plain Provinces. The golf courses used were chosen because they each contained a stream that entered the golf course at only one point and ran through a majority of the course before exiting the property. In addition, the streams were similar in terms of various physical and chemical parameters including width, depth, and substrate composition.

Four sample sites were established on each stream. Two of these sites were located upstream of the golf course; they were located just before or after the stream entered the golf course property. These sites were considered to be unimpacted by the golf courses. Two downstream sites were also established. These sites were located on the stream just before or after the stream exited the golf course property; these sites combined are referred to as the downstream location.

Only two golf courses, Course 1 and Course 3, were used for the pesticide and nutrient runoff studies. Course 1 was chosen because it is an intensively managed golf course and one that lacks a riparian zone along the edge of the stream. Course 3 was chosen because it is also an intensively managed course, but a riparian zone is maintained along the length of the stream. Frequency of sampling at the two courses was influenced by the timing, duration, intensity, and location of the storms that caused runoff events.

Pesticide Contamination Studies

Sample collection and processing

Water samples were collected following 5 runoff events during the summer and early fall of 1998 to determine if pesticides were moving from golf courses into surface waters via runoff. Water samples were collected four times from Course 1 on July 24, July 31, August 11, and October 8. On September 18 samples were collected from Course 3. Water samples were collected within 12 hours of major storm events, therefore the streams were still relatively swollen, assuring that the samples collected were runoff samples and not composed entirely of baseflow stream water.

Water samples were collected and processed using methods developed by personnel at the USDA Agricultural Research Service Environmental Chemistry Laboratory (11, 12, 30). In addition to the eight samples from the four field sites and the matrix spike, one deionized water blank and one deionized water blank spiked with a mixture of target analytes were also extracted and analyzed as controls. The water samples were processed using the SPE cartridges to extract pesticides on the same day as their collection.

Pesticide analysis

Ten pesticides were regularly used on the two golf courses. Of these, four pesticides were chosen for analysis due to their ability to be detected in water samples using gas chromatography and mass spectrometry. The four pesticides examined were pendimethalin, metalxyl, chloripyrifos, and chlorothalonil.

Analysis of spiked samples yielded acceptable recoveries of pesticides usually within 20% of expected concentration thereby verifying method recovery efficiency. In addition, pesticides were not detected in the field blank. There was no evidences of sample contamination through the transportation and collection process.

Data analysis

Pesticide concentrations in water samples collected from uptstream sites were compared to the concentrations in water samples from the downstream sites. The data from Course 1 and Course 3 were tested separately as were the concentrations of each of the pesticides. Data from both courses were analyzed for location effects. Finally, Tukey's contrasts were com;eted to determine if the concentrations of the pesticides in the upstream and downstream samples from Course 1 were significantly different for each of the sample dates.

Nutrient Contamination Studies

Regular sampling

Water samples for nutrient analysis were collected in conjunction with samples for pesticide analysis following five runoff events. In addition, samples were regularly collected from each of the courses one or two times a month over a 2-year period. Water samples for nutrient analysis were collected once or twice a month from each of the sampling sites at each golf course in 1998 and 1999.

Water samples were analyzed for nitrate, total phosphorus, and fluoride using a Hach Company (Loveland, Colorado) DR 890 colorimeter and its associated methods and reagents (9). Water samples were analyzed in the field for nitrate except during the winter months of January to March. During the winter months, water samples were brought back to the laboratory and allowed to warm to room temperature, at which point nitrate levels were measured. Water samples were analyzed for fluoride and total phosphorus in the laboratory.

Runoff sample analysis

Water samples were also collected following runoff events to determine if nutrients (nitrogen and phosphorus) moved into streams adjacent to golf courses via runoff. Due to the urgent need to return to the laboratory in order to process runoff water samples collected for pesticide analysis, samples collected for nutrient analysis were placed on ice and brought back to the laboratory for nitrate and fluoride analysis. Finally, in order to obtain more precise total phosphorus concentrations in water samples collected following runoff events, the samples were analyzed by the Nutrient Analytical Services at the Chesapeake Biological Laboratory in Solomons, Maryland.

Periphyton growth

Periphyton growth was measured in order to determine if there was any biological evidence of nutrient enrichment of the streams. Periphyton productivity was measured by allowing periphyton to grow on artificial substrates, in this case frosted acrylic plates. At the end of the 6-week colonization period, the plates were removed from the stream and all of the periphyton growing on the 4 plates at each location was collected. Ash-free dry mass (AFDM) of periphyton was determined using methods developed by Steinman and Lamberti (36).

Data analysis

Nitrate and total phosphorus concentrations of samples collected during regular sampling at upstream and downstream locations were analyzed in 3 ways. First, the overall impact of golf course fertilization was determined by comparing the mean nutrient concentrations from upstream and downstream locations (referred to as the overall analysis). In addition, nutrient concentrations at the upstream and downstream locations of each course were analyzed separately (referred to as the by course analysis). This analysis was completed to determine if there was any variation in the differences of nutrient concentrations between the upstream and downstream sites at different courses, thereby providing information on whether different management practices might have different effects of stream nutrient levels.

Finally, the mean nutrient concentrations of samples collected from upstream and downstream locations were compared for each season separately (referred to as the by season analysis) to determine if nutrient enrichment of the stream occurred during time periods (spring and fall) when fertilizers were applied in the highest amounts to golf courses. Only the overall and by course analyses of fluoride concentrations were completed.

Nitrate and total phosphorus concentrations in upstream and downstream runoff samples were analyzed to determine if their differences were significant. Runoff data from Courses 1 and 3 were analyzed for location effects. Tukey's contrasts were completed which compared the upstream and downstream concentrations for each sample date to identify significant changes in concentrations. Mean periphyton growth at the upstream and downstream locations was determined by averaging the AFDM of periphyton from both upstream and downstream sites. Mean AFDM and PAR from the upstream and downstream locations also was compared.

Benthic Macroinvertebrate Community Studies

Benthic macroinvertebrate community sampling

Benthic macroinvertebrates were collected five times in 1997 and five times in 1998. Macroinvertebrates were collected using artificial leafpack samplers. Five leafpacks, each consisting of five grams of dried oak leaves, were connected to bricks with a strap and placed in the stream three weeks prior to the sampling date to allow for colonization by benthic macroinvertebrates. On the sample date, the leafpacks were collected and returned to the laboratory for invertebrate identification. for invertebrate identification. After the invertebrates were isolated using the pan-trapping method, they were counted and identified. Only aquatic insects were counted and identified for analysis. Invertebrates from other taxonomic classes were discarded.

Physical and chemical parameters

Several physical and chemical stream parameters were measured at the time the leafpacks were collected from the stream. These parameters included alkalinity, hardness, photosynthetic active radiation (PAR), dissolved oxygen, pH, temperature, turbidity, conductivity, pH, and discharge information (current velocity, depth, width). Alkalinity, hardness, and turbidity of the stream water were usually measured in the field.

In 1997, dissolved oxygen was measured from different stream locations. Dissolved oxygen was immediately measured upon collection of the water from the stream. Stream pH and temperature were recorded. Conductivity was not measured in 1997. Dissoslved oxygen, pH, conductivity, and temperature were measured in 1998. Current velocity and depth were measured during both 1997 and 1998.

Data analysis

There are several different types of bioassessment indices including richness measures, enumerations, community diversity and similarity indices, biotic indices, and functional feeding-group measures. Included among these indices are enumerations (total abundance) and richness measures (taxa richness and Ephemeroptera, Plecoptera, and Trichoptera (EPT) richness). Total abundance was calculated for each location (upstream and downstream) from each of the courses on each of the sample dates. Total abundance was the total number of individuals collected using all of the recovered leafpacks at one location.

Taxa richness was calculated as the total number of different taxa collected using all of the leafpacks recovered from one location on each sampling date. EPT richness was calculated for each of the leaf packs. This value was the total number of Ephemeroptera (mayfly), Plecoptera (stonefly), and Trichoptera (caddisfly) taxa collected in one leafpack. The EPT richness value for a location was determined by averaging the EPT values of all recovered leafpacks from each location on each sampling date.

Benthic macroinvertebrate data was analyzed for an overall effect of golf course management practices on benthic macroinvertebrate communities by combining and analyzing data collected from the courses. The bioassessment indices were analyzed for location (upstream-vs-downstream) effects. The location effect was the effect of primary interest because it provided information about the change in the benthic communities between the locations. Benthic macroinvertebrate data was also analyzed for each course separately to compare the benthic communities from the upstream and downstream locations. This comparison was completed to identify specific management practices at each course that could impact the benthic communities. Finally, the physical and chemical parameters were analyzed to determine if the values of any of the parameters significantly differed between the upstream and downstream locations.

RESULTS

Pesticide Contamination Studies

Pesticides, while varying in their concentrations, were found in all water samples collected following runoff events. Chlorothalonil was detected in all of the water samples collected. In general, at Course 1 the concentration of chlorothalonil from water samples collected from the downstream location was similar to or slightly greater (although not significantly so) than that of samples collected from the upstream location (Table 1). However, in samples collected on July 31, 1998, the downstream sample concentration was significantly less than that of the upstream samples. The chlorothalonil concentration of water samples collected from the downstream location of Course 3 was significantly less than that of samples from the upstream location (Table1).

Chlorpyrifos was detected in water samples collected from Course 1 on all four sample dates. On three of the four sample dates, the chlorpyrifos concentrations were greater in downstream samples as compared to upstream samples (Table1) , and the difference was significant in samples collected on 8-October-1998. At Course 3, the concentration of chlorpyrifos in samples collected from the upstream location was significantly greater than that in samples collected from the downstream location (Table1).

Metalaxyl was detected in all water samples collected from Course 1, however the location that contained the higher concentration varied by sample date (Table1). The concentrations were

Chemical	Location	Course 1				Course 3
		7/24/98	7/31/98	8/11/98	10/8/98	9/18/98
Chlorothalonil	Upstream	5.53	**694.17**	3.01	1.81	4.38
	Downstream	9.66	31.03	5.66	2.29	2.53
Chlorpyrifos	Upstream	BQL	**31.4**	BQL	2.71	34.8
	Downstream	3.07	**39.36**	4.57	**679.15**	14.24
Metalaxyl	Upstream	6.64	211.27	7.18	ND	14.98
	Downstream	444.75	71.82	132.19	ND	12.12
Pendimethalin	Upstream	ND	ND	ND	ND	88.5
	Downstream	ND	138.53	ND	35.4	ND
Nitrate	Upstream	1.05	0.5	0.9	0.4	0.8
	Downstream	0.06	0.11	0.3	0.8	0.6
Total Phosphorus	Upstream	0.06	0.11	0.04	0.18	0.21
	Downstream	0.11	0.26	0.07	0.38	0.13

Note: Numbers in **bold** are estimates because their true concentration exceeded the uppper limit of the standard curve. BQL indicates that the concentration of the pestcide was below quantification limits. ND indicates the pesticide was not detected in the water sample.

Table 1. Concentrations of pesticides (nanograms/L) and nutrients (mg/L) in water samples collected following runoff events

significantly greater in samples collected from the downstream sites on July 24, 1998 and August 11, 1998. Metalaxyl concentrations were significantly lower in the downstream samples collected on July 31, 1998 and October 8, 1998. Metalaxyl concentrations did not significantly differ in the upstream and downstream samples collected from Course 3 (Table 1).

Pendimethalin was detected in only 2 of 4 water samples collected from Course 1. On both of these sample dates, pendimethalin was detected only in the downstream samples (Table1), and the increase between the upstream and downstream locations was significant (July 31, 1998 and October 8, 1998). Pendimethalin was detected only in the upstream samples collected from Course 3 (Table 1) and its concentration in the upstream samples was significantly greater than its concentration in the downstream samples.

Nutrient Contamination Studies

Nitrate analysis, regular sampling

Nitrate concentrations, when analyzed using data from all courses, were found to be significantly greater in samples collected upstream of the courses (Table 2). In addition, nitrate concentrations at each course were greater at the upstream locations, and for all of the courses except Course 2, the difference between the upstream and downstream locations was significant as revealed in the by course analysis (Table2). Finally, seasonal analysis of the data revealed that nitrate levels were significantly greater in samples collected from locations upstream of the golf course during each season,

Nutrient	Location	Overall	Course 1	Course 2	Course 3	Course 4
Nitrate[a]	Upstream	1.72	1.62	1.98	1.65	1.61
	Downstream	1.07	0.75	1.75	1.06	0.67
Phosphorus[b]	Upstream	0.53	0.49	0.54	0.40	0.65
	Downstream	0.54	0.54	0.52	0.42	0.65
Flouride[c]	Upstream	0.14	0.13	0.14	0.12	0.17
	Downstream	0.15	0.12	0.15	0.11	0.23

[a] mg NO_3^-/L
[b] mg PO_4^{-3}/L
[c] mg Fl^-/L

Table 2. Mean nutrient values (mg/L) caculated using data gathered from all courses (overall) and for each course.

including those in which fertilizers are applied to golf courses.

Total phosphorus analysis, regular sampling

Total phosphorus concentrations, as revealed by the overall analysis, at the upstream and downstream locations were similar (Table 2) and did not differ significantly. In addition, phosphorus concentrations of upstream and downstream samples were also similar (Table2). Finally, there were no significant differences in total phosphorus concentrations in samples collected from upstream and downstream locations during any season.

Flouride analysis, regular sampling

Fluoride concentrations were similar in samples from upstream and downstream locations as revealed by both the overall analysis and the by course analyses (Table 2).

Runoff water samples

Nitrate concentrations of Course 1 water samples collected from the upstream locations had higher concentrations than those collected from the downstream locations on July 24, 1998 and August 11, 1998. However, samples collected on July 31, 1998 and October 8, 1998 had lower nitrate concentrations in samples from the upstream (Table 1). Only on August 11, 1998 was the difference significant.

Total phosphorus concentrations were always greater in Course 1 water samples from the downstream locations, compared to those of the upstream locations (Table1). The increase in the total phosphorus levels between the upstream and downstream locations was significant in samples collected on July 31, 1998 and October 8, 1998.

Water samples collected from Course 3 on September 18, 1998 had higher concentrations of both nitrate and total phosphorus in samples collected from the upstream locations (Table 1), however, the differences were not statistically significant. Fluoride concentrations were approximately equal at allsites for all runoff events.

Periphton growth study

Mean ash-free dry mass (AFDM) of periphyton that colonized acrylic plates at locations upstream and downstream of the golf courses did not significantly differ. However, the AFDM of periphyton was generally greater from sites upstream of the golf courses. Mean PAR did not differ at the upstream and downstream locations.

Benthic Macroinvertebrate Community Studies

Artificial leafpacks were successfully used for the collection of benthic macroinvertebrates associated with organic matter in streams. Large numbers of individuals (42,557) and taxa (79) were collected allowing for the comparison of the communities at locations upstream and downstream of the golf courses.

Community structure was measured using three bioassessment indices: total abundance, taxa richness, and EPT richness. Analysis of the data revealed a significant increase in the total abundance of benthic invertebrates at the downstream locations (Table 3). Taxa richness was also significantly greater at the downstream locations (Table3). Finally, while the mean EPT richness values of the downstream locations were usually greater than that of the upstream location (Table3), there was no significant difference in the means. The FBI values from the upstream and downstream locations were similar and the analysis revealed no significant differences (Table 3), indicating no difference in the degree of organic pollution between the two locations.

Data on each of the biotic indices from each of the courses was analyzed separately in order to determine if changes in the benthic community at any one stream might be related to management practices used at that particular golf course. A significant increase in total abundance at the downstream locations was detected for Course 2 and Course 3. In addition, there was a significant increase in the taxa richness at the downstream location of Course 2. Significant

Bioassessment Index	Location	Overall	Course 1	Course 2	Course 3	Course 4	Course 5
EPT Richness	Upstream	0.53	0.75	0.24	0.75	0.98	0.6
	Downstream	0.94	0.6	0.62	1.13	1.25	0.5
Taxa Richness	Upstream	7.07	7.9	4.44	9.2	8.4	7.2
	Downstream	9.59	8.6	7.22	12.5	8.2	5.4
Total Individuals	Upstream	0.18	0.12	0.14	0.12	0.12	0.11
	Downstream	0.24	0.12	0.2	0.2	0.13	0.13
Hilsenhoff FBI	Upstream	5.72	5.42	5.95	5.85	5.77	5.53
	Downstream	5.81	6.00	5.86	5.68	5.74	5.75

Note: Data was transformed using the natural log of the original value plus one.

Table 3. Mean bioassessment indices calculated using dta gathered from all courses (overall) and for each course

increases in the EPT richness at the downstream location occurred at Course 2 and Course 3. Finally, analysis of the FBI data revealed significant decreases at the downstream location at Course 2 and Course 3. No other significant differences were detected for any of the bioassessment indices at any of the courses.

Analysis of the physical and chemical data revealed no significant difference in the values of any of the parameters when upstream and downstream locations were compared. The values for each of the physical and chemical parameters at the upstream and downstream locations were also compared for each course separately to determine if any changes in the benthic community between the upstream and downstream locations at any of the courses could be explained by a change in the physical and chemical parameters of the stream. There were significant increases in alkalinity and hardness at the downstream location of Course 1. Course 3 had a significant increase in hardness at the downstream location No other differences were found in any of the parameters at any of the courses.

DISCUSSION

Results of this study indicate that the structure of the benthic macroinvertebrate communities at locations upstream and downstream of golf courses differs (Table 3). In general, total abundance and taxa richness of benthic macroinvertebrates collected at locations downstream of the golf courses was greater than that collected at locations upstream of the courses. In addition, EPT richness was usually greater, although not significantly so, at sites downstream of the golf courses. Finally, while the taxa most commonly collected at the upstream and downstream sites were the same, the number of individuals of these taxa collected from the downstream locations was greater than the number collected from the upstream sites for each of the taxa.

When the benthic macroinvertebrate communities of each of the golf courses were analyzed separately, similar results were obtained for Courses 2 and 3. Total abundance and EPT richness were significantly greater at the downstream locations of these courses. Taxa richness was also greater at the downstream locations of these two courses.

While changes in the benthic macroinvertebrate communities between the upstream and downstream locations were found, it is difficult to relate these changes to golf course management practices. For instance, pesticide contamination and severe nutrient enrichment (e.g., eutrophication) should be correlated with decreases in total abundance, taxa richness, and EPT richness, as well as an increase in FBI values (7, 16, 31. However, the results of this research indicated increases in total abundance, taxa richness, and EPT richness at the downstream locations that are sites that could be impacted by golf course management practices including pesticide and fertilizer applications.

Pesticide concentrations of streams associated with Course 1 and Course 3 were measured following five runoff events in 1998. In general, at Course 1 pesticide concentrations were higher at the sites downstream of the golf course (Table 1). However, at the same time that pesticides were detected in higher concentrations at the downstream location, EPT richness and taxa richness values were higher at the downstream location and the FBI value was either lower at the downstream location or the same at both locations. Pesticide contamination of a stream, at concentrations great enough to affect the benthic community, would be expected to cause a decrease in EPT and taxa richness, and an increase in FBI values. Therefore, pesticide application to golf courses does not appear to explain the shifts in the benthic macroinvertebrate community.

An increase in the productivity of aquatic organisms can be seen with slight nutrient enrichment. Freshwater ecosystems are usually nutrient limited (6). Therefore, moderate nutrient input may actually increase productivity of an aquatic ecosystem. It is possible that the increase in total abundance and taxa richness at the downstream locations might be due to some moderate level of nutrient enrichment of the stream by the golf course. However, research completed as part of this project found significant decreases in nitrate concentrations at sites downstream of the golf courses. In addition, the total phosphorus concentration of the streams did not differ between the upstream and downstream locations (Table 2). Since nutrients, mainly phosphorus, are limiting factors in terms of the biological productivity of freshwater ecosystems (13), additional inputs of nutrients are normally utilized by the biota. Therefore, analysis of nutrient concentrations in water samples may not provide evidence of nutrient enrichment, when in fact, enrichment of the system is occurring.

Measurement of the biological productivity of the stream can often provide evidence of enrichment even when this is not seen in chemical analysis of water samples. Periphyton productivity is commonly measured as an indicator of biological productivity, as demonstrated in experiments completed by Hepinstall and Fuller (13) and McCormick and O'Dell (21) among others. In this study, periphyton productivity did not differ significantly at sites upstream and downstream of the courses. In fact, there was greater periphyton growth at the upstream locations (Table 2). Therefore, the application of fertilizers to golf courses does not appear to cause nutrient enrichment of adjacent streams, nor does it appear to influence the biological productivity, including that of the benthic communities, of these streams.

While there are other possible explanations for the changes in the benthic community between the upstream and downstream locations (e.g., changes in substrate, undetected physical or chemical changes, etc.) the results of the benthic macroinvertebrate community study and the stream nutrient enrichment study reveal one possible explanation for the overall changes found in the benthic macroinvertebrate community, and the shifts seen at Course 2 and Course 3. The differences in the communities may reflect lower organic pollution (including nutrient loading) at sites downstream of the golf course.

The Hilsenhoff FBI, which is used to indicate organic pollution, is calculated using tolerance values for benthic taxa. More tolerant taxa have higher tolerance values, thereby leading to higher FBI values. A decrease in the FBI value can then indicate an increase in sensitive species with lower tolerance values (an increase in sensitive species). At both courses, the Hilsenhoff FBI was significantly lower at the downstream sites (Table 3), indicating the presence of more pollution sensitive taxa at these sites. Therefore, since the Hilsenhoff FBI at the downstream location is significantly less than that of the upstream location, higher water quality and a decrease in organic pollution downstream of the golf course is indicated.

Pesticides and nutrients were detected in surface waters adjacent to golf courses. However, the results of analysis of samples from different courses yielded different results. In general, at Course 1, pesticide concentrations were greater in samples collected downstream of the course (Table 1). Results of the analysis of water samples from Course 3 showed trends opposite to those found in Course 1 water samples. Pesticide concentrations from Course 3 water samples were consistently greater at the upstream sites (Table 1). While it is not possible, on the basis of this data and experimental design, to conclude that pesticides were not moving into the stream by runoff from Course 3, it is possible to conclude that the amount of pesticides moving into the stream was not great enough to increase the overall concentration of the pesticides above the level with which the stream entered the golf course property.

In addition, although it does not appear as though golf course fertilizer applications are a source of long-term nutrient enrichment of streams, nutrient concentrations of water samples collected from Course 1 following runoff events suggests that phosphorus, and occasionally nitrate, moved into the stream through runoff. At Course 3, nitrate and total phosphorus concentrations of samples collected following runoff events from sites downstream of Course 3 were lower than those of samples collected from the sites upstream of this course.

On the basis of this data, it is apparent that, in some cases (e.g., Course 1), contamination of

Increases in water quality at the downstream location may, in fact, indicate that not only are the golf courses not having a deleterious effect on the streams (i.e., the addition of pollutants), but also that the streams are actually cleaner when they leave the golf courses than they were entering the golf course property.

streams adjacent to golf courses by pesticides is occurring in association with runoff events. However, the amount of stream contamination by pesticides varied by golf course and runoff event. The extent of the contamination appears to be influenced by several factors. One of these factors appears to be the amount of rain generated during the storm event. The highest pesticide concentrations, and in the case of chlorpyrifos and pendimethalin, the largest increases in pesticide concentrations between the upstream to downstream sites were detected in water samples collected on July 31, 1998 and October 8, 1998.

In addition, nitrate and total phosphorus concentrations were greater in the downstream samples on the same two dates. These were the sampling dates on which the most rainfall was recorded. Similar findings were made by Sudo and Kunimatsu (37): pesticide concentrations in water samples increased with increasing discharge.

While there are several possible explanations for the differences in the runoff trends at Course 1 and Course 3, we are going to address only 2. One possible explanation could be differences in the amount of precipitation generated during the different runoff events or at the different courses. However, since the precipitation generated by the storms at Course 3 on September 18, 1998 and Course 1 on July 31, 1998 and October 8, 1998 was approximately the same, differences in the amount of rainfall are not likely explanations for differences in the results obtained at Course 1 and Course 3 (e.g., higher concentrations downstream at Course 1 and upstream at Course 3).

A factor we believe may explain the difference in results from the two courses is the presence of a buffer zone that minimizes runoff into a stream. Course 1 mows the turf to the stream's edge, thereby removing any buffer zone or protective vegetative strip. This, in effect, removes any barrier that might protect the stream from contamination by pesticide-contaminated runoff. Course 3, on the other hand, maintains a well-developed buffer zone along the length of the stream. The presence of a buffer zone at Course 3 probably serves to prevent runoff from entering the stream, or minimizing the amount that is able to do so, thereby protecting the stream from contamination.

While some of the results of this study indicate that the benthic macroinvertebrate community changes between upstream and downstream locations occurred, there is no evidence that golf course management practices are the cause of these changes. Although pesticide contamination of the stream at one golf course was detected, it could not be linked to a deleterious effect on the benthic macroinvertebrates (e.g., a loss of taxa, EPT richness, or total abundance at contaminated sites).

Furthermore, long-term nutrient enrichment of streams associated with golf courses from the golf courses was not found. Therefore, nutrient enrichment of the streams by the golf courses is not a feasible explanation for the changes in the benthic community. Instead the changes in the community maybe the result of an increase in water quality at the downstream locations. Increases in water quality at the downstream location may, in fact, indicate that not only are the golf courses not having a deleterious effect on the streams (i.e., the addition of pollutants), but also that the streams are actually cleaner after they leave the golf courses.

All streams utilized in this study were urban streams, and therefore already impacted by runoff from developed areas (i.e. housing, shopping centers, roads, etc.). Thus, the streams contained contaminants, including pesticides and nutrients, before they entered the property of the golf courses. It is entirely possible that as the streams flow through the golf courses pollutants are able to move out of the system (e.g., nutrients may be utilized by aquatic organisms) and in the absence of additional inputs from the golf course, the pollutant levels in the stream as they leave the golf courses are lower. Therefore, it appears as though golf course management practices, including the environmentally sound use of pesticides and fertilizers, pose little threat to the integrity of aquatic communities of surface waters adjacent to golf courses.

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Literature Cited

1. Brock, T.C.M., R.M.M. Roijackers, R. Rollon, F. Bransen, and L. Van der Heyden. 1995. Effects of nutrient loading and insecticide application on the ecology of *Elodea*-dominated freshwater microcosms II. Responses of macrophytes, periphyton, and macroinvertebrate grazers. *Arch. Hydrobiol.*134(1): 53-74.

2. Brown, K.W., J.C. Thomas, and R.L. Duble. 1982. Nitrogen source effect on nitrate and ammonium leaching and runoff losses fromgreens. *Agron. J.* 74:947-950. (TGIF Record 502)

3. Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecol. Applic.* 8(3):559-568.

4. Carroll, M.J. 1993. Protecting groundwater supplies: Determining pesticide mobility and persistence in soil. *Golf Course Management* 61(6):103-107. (TGIF Record 27741)

5. Cuppen, J.G.M., R. Gylstra, S. van Beusekom, B.J. Budde, and T.C.M. Brock. 1995. Effects of nutrient loading and insecticide application on the

ecology of *Elodea*-dominated freshwater microcosms, III: Response of macroinvertebrate detritivores, breakdown of plant litter, and final conclusions. *Arch. Hydrobiol*. 134(2):157-177.

6. Elser, J.J., E.R. Marzolf, and C.R. Goldman. 1990. Phosphorus and nitrogen limitation of phytoplankton growth in the freshwaters of North America: A review and critique of experimental enrichments. *Can. J. of Fish. and Aquat. Sci*.47:1468-1477.

7. Fairchild, J.F., T.W. LaPoint, J.L. Zajicek, M.K. Nelson, F.J. Dwyer, and P.A. Lovely. 1992. Population-, community- and ecosystem-level responses of aquatic mesocosms to pulsed doses of a pyrethroid insecticide. *Environ. Toxicol. and Chem*. 11:115-129.

8. Gross, C.M., J.S. Angle, R.L. Hill, and M.S. Welterlen. 1991. Runoff and sediment losses from tall fescue under simulated rainfall. *J. Environ. Qual*. 20(3):604-607. (TGIF Record 28046)

9. Hach. 1997. Hach Company DR/890 Colorimeter Procedures Manual (Revised Version 1, 12/97). Hach Company, Loveland, Colorado.

10. Hach. 1996. Hach Company Digial Titrator Model 16900 Manual 21ed. HACH Company, Loveland, Colorado.

11. Harman, J.A. 1996. Fate and transport of agricultural pesticides in the Patuxent River, a subestuary of the Chesapeake Bay. M.S. thesis, Univeristy of Maryland.

12. Harman-Fetcho, J.A., L.L. McConnell, and J.E. Baker. 1999. Agricultural pesticides in the Patuxent River, a tributary of the Chesapeake Bay. *J. Environ. Qual*. 28:928-938.

13. Hepinstall, J.A., and R.L. Fuller. 1994. Periphyton reactions to different light and nutrient levels and the response of bacerial to these manipulations. *Arch. Hydrobiol*. 131(2):161-173.

14. Hilsenhoff, W.L. 1988. Rapid field assessment of organic pollution with a family-level biotic index. *J. N. Am. Benthol. Soc*. 7(1):65-68.

15. Hong, S., and A.E. Smith. 1997. Potential movement of dithiopyr following application to golf courses. *J. Environ. Qual*. 26:379-386. (TGIF Record 39802)

16. Johnson, R.K., T. Wiederholm, and D.M. Rosenberg. 1993. Introduction to freshwater biomonitoring and benthic macroinvertebrates. *In* D.M. Rosenberg and V.H. Resh (eds.), Freshwater biomonitoring and benthic macroinvertebrates. Routledge, Chapman, and Hall, New York.

17. Kenna, M.P. 1995. What happens to pesticides applied to golf courses? *USGA Green Section Record* 33:1-9. (TGIF Record 32638)

18. Kersting, K., and P.J. Van Den Brink. 1997. Effects of the insecticide Dursban®4E (active ingredient chlorpyrifos) in outdoor experimental ditches: Response of ecosystem metabolism. *Environ. Toxicol. Chem*. 16(2):251-259. (TGIF Record 94119)

19. LaMotte. 1996. LaMotte turbidity in water instructions. LaMotte Company, Chestertown, Maryland.

20. Lehotay, S.J., J.A. Harman-Fetcho, and L.L. McConnell. 1998. Agricultural pesticide residues in oysters and water from two Chesapeake Bay Tributaries. *Mar. Pollut. Bull*. 37(1-2):32-44.

21. McCormick, P.V., and M.B. Odell. 1996. Quantifying periphyton responses to phosphorus in the Florida Everglades: A synoptic-experimental approach. *J. N. Am. Benthol. Soc*. 15(4): 450-468.

22. McKinney, R. 1993. Environmental regulations. *TurfGrass Trends*, December issue:1-6. (TGIF Record 37256)

23. Miles, C.J., G. Leong, and S. Dollar. 1992.

Pesticides in marine sediments associated with golf course runoff. *Bull. Environ. Contam. Toxicol.* 49:179-185. (TGIF Record 31072)

24. Mol, A. 1980. The role of the invertebrate fauna in the biological assessment of water quality . *Hydrobiologia Bulletin* 14(3): 222-223.

25. Morse, J.C., B.P. Stark, and W.P. McCafferty. 1993. Southern Appalachian streams at risk: implications for mayflies, stoneflies, caddisflies, and other aquatic biota. *Aquat. Conserv*. 3:293-303.

26. Morton, T.G., A.J. Gold, and W.M. Sullivan. 1988. Influence of overwatering and fertilization on nitrogen losses from home lawns. *J. Environ. Qual.* 17(1):124-130. (TGIF Record 12590)

27. Niederhauser, P., and F. Schanz. 1993. Effects of nutrient (N, P, C) enrichment upon the littoral diatom community of an oligotrophic high-mountain lake. *Hydrobiologia* 269/270:453-462.

28. Peacock, C.H., and M.M. Smart. 1995. IPM, monitoring, and management plans - A mandate for the future. *USGA Green Section Record* 33:10-14. (TGIF Record 33612)

29. Petrovic, A.M. 1990. The fate of nitrogenous fertilizers applied to turfgrass. *J. Environ. Qual.* 19(1):1-14. (TGIF Record 16975)

30. Rader, R.B., and C.J. Richardson. 1994. Response of macroinvertebrates and small fish to nutrient enrichment in the northern Everglades. *Wetlands* 14(2):134-146.

31. Resh, V.H., and J.K. Jackson. 1993. Rapid assessment approaches to biomonitoring using benthic macroinvertebrates. *In* D.M. Rosenberg and V.H. Resh (eds.), Freshwater biomonitoring and benthic macroinvertebrates. Routledge, Chapman, and Hall, New York.

32. Rosenberg, D.M. and V.H. Resh. 1996. Use of Aquatic Insects in Biomonitoring. *In* R. W. Merritt and K.W. Cummins (eds.). An introduction to the aquatic insects of North America, 3rd ed. Kendall/Hunt Publ. Co., Dubuque.

33. Rosenberg, D.M., and V.H. Resh. 1993. Introduction to freshwater biomonitoring and benthic macroinvertebrates. *In* D.M. Rosenberg and V.H. Resh (eds.). Freshwater biomonitoring and benthic macroinvertebrates. Routledge, Chapman, and Hall, New York.

34. Ryals, S.C., M.B. Genter, and R.B. Leidy. 1998. Assessment of surface water quality on three eastern North Carolina golf courses. *Environ. Toxicol. Chem.* 17(10):1934-1942. (TGIF Record 66409)

35. Smith, A. 1995. Potential movement of pesticides following application to golf courses. *USGA Green Section Record* 33(1):13-14. (TGIF Record 32656)

36. Steinman, A.D. and G.A. Lamberti. 1996. Biomass and pigments of benthic algae. *In* F.R. Hauer and G.A. Lamberti (eds). Methods in stream ecology. Academic Press, San Diego.

37. Sudo, M., and T. Kunimatsu. 1992. Characteristics of pesticides runoff from golf links. *Water Sci. Tech.* 25:85-92. (TGIF Record 94118)

38. Van Es, H. M. 1990. Pesticide management for water quality: Principles and practices. Department of Soil, Crop, and Atmospheric Sciences Extension Series No.1, Cornell Cooperative Extension.

39. Watschke, T.L., S. Harrison, and G. W. Hamilton. 1989. Does fertilizer/pesticide use on a golf course put water resources in peril? *USGA Green Section Record* 27:5-8. (TGIF Record 14834)

40. Wiggins, G.B. 1996. Larvae of the North American caddisfly genera (Trichoptera), 2nd

Edition. University of Toronto Press, Toronto.

41. Willis, G.H., and L.L. McDowell. 1982. Review: Pesticides in agricultural runoff and their effects on downstream water quality. *Environ. Toxicol. Chem.* 1:267-279.

42. Winterbourn, M.J. 1990. Interactions among nutrients, algae, and invertebrates in a New Zealand mountain stream. *Freshwater Biol.* 23:463-474.