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Effects of haying and agricultural practices on a declining species: The North American wood turtle, *Glyptemys insculpta*

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ABSTRACT

In North America, the spatio-temporal scale of deforestation has resulted in a 94% decrease in temperate forests within 360 years. Despite the enormous scale of this disturbance, agriculture is so pervasive in modern society that its impacts are highly underappreciated. We investigated the impact of current agricultural practices on a disturbance-dependent species in southern Québec, Canada. Of 30 wood turtles (*Glyptemys insculpta*) followed via radio-telemetry, 20% died as a result of agricultural activities. Anthropogenic mortality estimates for adults and juveniles in 1998 were 0.10 and 0.18, respectively. For 1999, these values were 0.13 and 0.17, respectively. Of those turtles that survived, many had injuries inflicted by agricultural machinery. Sub-lethal mutilation rates for adults were 90 ± 3% in both years, whereas the maximum frequency for juveniles was 57%. A Carapace Mutilation Index was derived to quantify the distribution and severity of injuries observed. Only male and juvenile Carapace Mutilation Index values differed significantly. Adults had significantly more carapace injuries and limb amputations on their right sides. This bilateral asymmetry of injuries resulted from of a combination of turtle flight behavior and traditional harvesting practices. We reiterate the recommendations of forage researchers: setting the cutting height of disc mowers to 100 mm increases harvest yields, reduces wear on machinery, and decreases soil erosion. A by-product of such a change in cutting height is that turtle mortality and injury rates should be reduced, as wood turtle carapace height is <87 mm. Without changes in agricultural practices, this population will be extirpated.

1. Introduction

North America offers a unique opportunity to investigate the spatio-temporal impacts of agricultural development on wildlife. Native American peoples have been engaged in small-scale gardening within the eastern woodlands of North America for approximately 4000 years, whereas large-scale farming and crop storage have been well established for only the last 1000 years in this region (Hammett, 1992; Scarry, 1993; Yarnell, 1993). Although agrarian Native American peoples and wildlife have co-existed for millennia, agricultural practices have changed considerably since the arrival of the first European colonists in the early 1600s (Hammett, 1992). Advances in agricultural machinery have played a central role in accelerating the rate of habitat destruction and modification. Aldo Leopold once wrote, "As for diversity, what remains of our native fauna and flora remains only because agriculture has not got around to destroying it" (Leopold, 1953).

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Although such a statement may seem harsh, it is not far from the truth. Of the estimated 170 million ha of temperate forest present in 1620, only 10 million ha remained by the 1980s as a result of deforestation (Goudie, 1990). Thus, the spatio-temporal scale of this exogenous disturbance was a 94% decrease in temperate forests within 360 years. Despite the enormous scale of this disturbance to the North American landscape, agricultural development is so pervasive in modern society that the intensity and spatial extent of its impacts are highly underappreciated. This is because the temporal scale of the aforementioned deforestation is greater than that of a human lifespan, resulting in a lack of historical perspective. Consequently, humans view that which was present upon initial observation as natural or normal (Dodd and Franz, 1993). Such a change in perception over time has been termed the "shifting baseline syndrome" (Pauly, 1995; Jackson, 2001; Jackson et al., 2001).

Agricultural machinery is responsible for other, more direct impacts upon wildlife. For instance, early agricultural studies focused on how agricultural machinery affected commercially important game birds in North America. The introduced ring-necked pheasant (*Phasianus colchicus*) benefited from agricultural practices in North America prior to the 1930s (Warner and Etter, 1989). Thereafter, tractor-powered cutter bars were recognized as a serious threat to reproductive females nesting in hayfields, with an average of 65% of pheasants being struck by haying machinery while incubating nests (Warner and Etter, 1989). Other studies determined that hay mowers destroyed 56–83% of waterfowl nests (Labisky, 1957; Gates, 1965). Recently, ornithologists have realized that non-gamebird species are also declining in agricultural landscapes (Sotherton, 1998; Bradbury and Kirby, 2006). For example, research in northern Illinois suggested that bobolink (*Dolichonyx oryzivorus*) populations declined by >90% from 1966 to 1992 (Herkert, 1997).

Our study sought to investigate the impact of agricultural practices and machinery on a declining species with substantially lower vagility than avian fauna: the North American wood turtle, *Glyptemys insculpta* (Le Conte, 1830). This species is an ideal study organism because of its longevity, site fidelity, and low vagility (Garber and Burger, 1995). Moreover, Kaufmann (1992a) speculated that *G. insculpta* might benefit from the increased habitat heterogeneity created by agricultural development. *Glyptemys insculpta* is characterized best as a disturbance-dependent species, as openings in the forest canopy are required for thermoregulation, egg incubation, and some foraging (Kaufmann, 1992a; Compton et al., 2002; Arvisais et al., 2004). Today, such a propensity to occupy disturbed terrestrial habitats exposes *G. insculpta* to significant risk. For instance, Saumure and Bider (1998) concluded that agricultural development likely resulted in increased adult mortality, as well as reduced predation, growth, and recruitment rates. For millennia, turtles have relied on the protection afforded them by an armoured shell, an adaptation quickly becoming obsolete in a world of passenger vehicles and agricultural machinery.

The potential impact of current agricultural practices and machinery on turtles and tortoises has not been adequately addressed. Thus, the present study investigated the impact of agricultural activities on a population of *G. insculpta* inhabiting an agri-forest landscape. The specific objectives were to determine rates and causes of mortality, as well as the frequency, pattern, and sources of injuries. In addition, we wished to develop a standardized method to quantify the severity of injuries in turtles. The final objective was to produce a series of management recommendations based on the results of the study.

2. Methods

2.1. Study site and species

The study site is located along 6.3 km of meandering river flowing north–south at an undisclosed locality in Brome County, Québec, Canada. The site encompasses 330 ha of privately owned land, which includes seven farms, 103 ha of which is deciduous forest. Cattle pastures, cash crops (i.e., hay, corn, and oats), and oldfields account for 177 ha of the remaining agri-forest landscape. Hayfields border 3.1 km of the river. As a result of the historical removal of riparian vegetation, erosion along fields and pastures is extensive. To alleviate the erosion problem temporarily, approximately 1.5 linear km of the river was dredged in 1999 and the gravel used to shore up the banks. The main river is bordered by a railroad track to the east and a paved road to the west, both of which run parallel to the river at distances ranging from 20 to 640 m. Specific habitat characteristics have been described elsewhere (Daigle, 1997; Saumure and Bider, 1998; Daigle and Jutras, 2005).

Glyptemys insculpta occur from Virginia north to Nova Scotia, and west through the Great Lakes region to Minnesota (Ernst et al., 1994). They are semi-aquatic, with populations centered upon small rivers and streams characterized by sand or gravel substrates, relatively clear waters, and slow to moderate currents. Riparian habitats frequented include various types of forests, meadows, bogs, swamps, fields, and pastures (Harding and Bloomer, 1979). *Glyptemys insculpta* populations are declining throughout their range as a direct result of such anthropogenic activities as habitat destruction, vehicular traffic, and collecting (Harding and Bloomer, 1979; Garber and Burger, 1995; Ernst, 2001).

We captured *G. insculpta* by hand during the 1995 and 1998–1999 field seasons. Turtles were marked, aged, sexed, measured, and photographed as described in Saumure and Bider (1998). In addition, we determined the maximum carapace height of every turtle recaptured in 1999 using Haglof tree calipers (±1 mm). Carapace height was defined as the maximum height of the entire shell as measured perpendicular to the plastron as per Mosimann and Bider (1960). Injuries were recorded as previously described in Saumure and Bider (1998). Injuries that resulted in death of a given turtle were excluded from mutilation analyses. We conducted post-harvest field surveys to locate any dead turtles that were not part of our telemetry sample.

2.2. Radio-telemetry

We equipped turtles with radio-transmitters (Holohil Systems Ltd., Ontario, Canada) during the 1998–1999 field seasons.

Twenty adult turtles were equipped with transmitters (Model AI-2) that were encased in brass cylinders and bolted to the posterior right marginal scutes. Neither movement nor copulation is compromised by this low-profile transmitter placement (Kaufmann, 1992b, personal observations). The complete transmitter assembly weighed 32.5 g. Five adults and five juveniles were equipped with glue-on transmitters (Model RI-2Csp). The transmitters were immobilized on the posterior carapace with 5-min epoxy and then sealed with PC-7®, a waterproof epoxy resin (Protective Coating Co., PA, USA). This dual epoxy technique proved ideal. These transmitters, including epoxy, weighed ⩽13 g and remained firmly attached for >2 years. Post-attachment transmitter mass ranged from 1 to 4.5% of turtle body mass. Minimum battery life for both transmitter models was two years. We located each turtle once or twice per week with an LA-12Q receiver (AVM Instrument Company Ltd., CA, USA) and a collapsible three-element Yagi antenna (AF Antronics, IL, USA). In addition, 12 of the 13 males tracked in 1999 were monitored sporadically during May–August 2000 as part of an additional study (Saumure, 2004). Transmitters removed from dead turtles were re-used. We preserved the remains of several turtles and deposited them as voucher specimens in the Canadian Museum of Nature herpetology collection.

2.3. *Survivorship*

We used the computer program MARK to calculate survivorship (S) from radio-telemetry data (White and Burnham, 1999). Mark-recapture data were not used to estimate survivorship because of low recapture probabilities, opportunistic sampling, and small sample sizes. Analyses of the radio-telemetry sample were conducted using information-theoretic methods (Anderson et al., 2000, 2001b). The 'known fate' radio-telemetry data gathered were compiled into two groups (i.e., g = adults and juveniles) of monthly encounter histories. Known fate data assume that the probabilities of live recapture (p) and dead reporting (r) equal 1.0. Second order Akaike's Information Criterion (AIC_c) and Akaike weights (w_i) were used to isolate the most parsimonious models based on minimization of the AIC_c (White and Burnham, 1999). The sin link function was used for all analyses. The w_i values were interpreted to be the relative degree of certainty that a given model is the best (Anderson et al., 2001a). As no one model had strong support ($w_i > 0.9$), model averaging was used to calculate weighted averages of the best models. Monthly survivorship was converted to an annual survival probability with the formula $\widehat{S}^x$, where $\widehat{S}$ is monthly survivorship and x is number of monthly sampling occasions. Mortality is defined as $1 - S$. Model notations follow those of Anderson et al. (2000).

2.4. *Injuries*

To date, most studies have reported only the prevalence of injuries within a given *G. insculpta* population (Brooks et al., 1992). Others have endeavored to compile the prevalence of injuries at specific morphological locations (Saumure and Bider, 1998; Walde et al., 2003). In order to standardize and quantify analyses of the severity of injuries, we derived a Carapace Mutilation Index. The carapace was chosen because of: (i) the defensive function it serves, (ii) the large prominent surface area, (iii) the persistence of old injuries, and (iv) the high number of carapace injuries previously reported (Saumure and Bider, 1998). To calculate the Carapace Mutilation Index, the carapace was subdivided into four distinct numbered quadrants (Fig. 1). The levels of injury sustained in each quadrant were then assigned the following qualitative values: intact = 0; minor = 1; moderate = 2; and severe = 3. Minor injuries were defined as small scrapes, scratches, and gouges confined to the scute layer of the shell. Such injuries are most often found on the marginal scutes. Moderate injuries were defined as large areas of damage confined to the scute layer; as well as small cracks, dents, and gouges that damaged both the bone and scute layers. In addition, moderate injuries included sections of marginal scutes that were missing. Severe injuries were defined as large gouges, clefts, and shell fractures not confined solely to the marginal scute area. Injuries that damaged the neural bones of the vertebral column and/or exposed the turtles' internal organs also were categorized as severe. In each turtle, the highest level of injury was recorded for each of the four quadrants; these values were then summed. The summed values, which can theoretically range between 0 and 12, were divided by 12 in order to create a Carapace Mutilation Index value between 0 and 1.

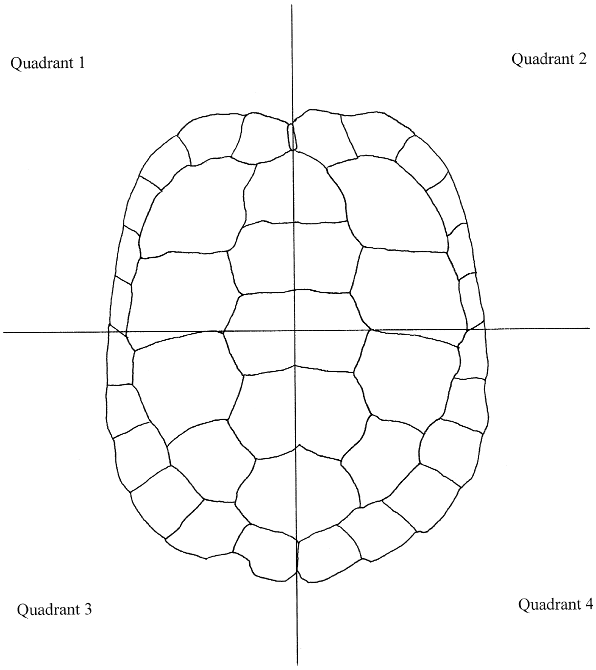

Fig. 1 – Carapace Mutilation Index quadrants for calculating the severity of injuries sustained by turtles.

The Mann–Whitney *U*-test was used for pair-wise comparisons because of the non-normality of Carapace Mutilation Index values. The Wilcoxon signed ranks test was used to test for the non-random distribution of the more serious levels 2 and 3 carapace injuries of adults. Specifically, we tested for lateral (left–right) and anterior–posterior differences in Carapace Mutilation Index values.

3. Results

3.1. Subjects

Sixty-six *G. insculpta* (22 males, 28 females, and 16 juveniles) were captured 978 times during the combined 1995 and 1998–1999 field seasons; 42 individuals (15 males, 18 females, and 9 juveniles) during the 1998–1999 field seasons. Of 52 individual turtles captured in 1995 (Daigle, 1997; Saumure and Bider, 1998), only 59.6% ($n = 31$) were recaptured during 1998–1999 despite a 12-fold increase in sampling effort. Overall, the number of individuals captured between 1995 and 1998–1999 declined by 19.2%. Thirty turtles (13 males, 12 females, and 5 juveniles) were equipped with transmitters during 1998–1999. Two of these turtles (1 male and 1 female) had limb amputations, as defined by Harding (1985). The number of turtles tracked at any one time varied from 20 to 26, depending upon capture effort and mortality. Turtles were monitored for periods ranging from 51 to 507 days. Shorter tracking periods were due to mortality.

The male: female sex ratio (0.83:1) for the 33 adult turtles captured in 1998–99 did not differ significantly from 1:1 ($\chi^2 = 0.27$, $P > 0.05$). The ratio of adults to juveniles was 3.67:1 for 1998–99. Mean carapace height ± standard deviation (range) for 31 adults (15 males and 16 females) was 74.17 mm ± 5.35 (65–82 mm) and 73.06 mm ± 4.13 (63–79 mm) for males and females, respectively. There were no intersexual differences in adult carapace height at this site ($t = -0.646$, df = 29, $P = 0.524$). As one would expect, carapace height for seven juveniles was significantly less than for adults: 52.36 mm ± 8.20 (41–61 mm).

3.2. Agricultural activities

Two new landowners converted hayfields and leased pastures to corn production during 1998–1999. Haying occurred twice each summer. Harvest was dependent upon weather, but generally took place over several days. In 1998–1999, the first harvest period occurred during the last few days of June and the first week of July. The second harvest occurred during the last few days of August and the first week of September. Hayfields were cut with either sicklebar or rotary disc mowers, after which tedders (i.e., a series of rotating steel tines that stir, fluff, and spread the swath of hay) were used to accelerate drying time. Finally, rakes and hay balers were used to complete the removal.

3.3. Survivorship

Of the 30 turtles tracked in 1998–2000, six died because of agricultural activities; none died of natural causes. Turtles were killed during June–August. Mortality was 20% ($n = 6$) of the 1998–2000 telemetry sample (3 males, 1 female, and 2 juveniles). Of these, four turtles (13.3%) are known to have died because of impacts with rotary disc mowers. Mower deaths occurred on only two of the seven farms, both of which used disc mowers. Severely mutilated males were recovered from hayfields in July 1998 and 1999. One male was severed completely in half, with an irregular fracture running transversely from the posterior right marginals to the marginals over the left bridge. A second male clearly revealed the dorso-lateral path of the disc mower blade on the right side of the carapace (Fig. 2). One female sustained injuries to the posterior left and anterior right limbs in June 1999. In addition, this turtle likely sustained internal injuries; when initially discovered it was bleeding from the mouth and the following day it was found dead in the field. A seventh mortality was reported to us by a farmer who had hit the specimen with a disc mower during haying in July 1999. Moreover, the farmer observed a coyote remove the carcass later the same evening. This was the third report of *G. insculpta* mortality on this particular farm in 1998–1999. All surviving turtles tracked during 1998–1999 had returned to the river by the time the second harvests had begun.

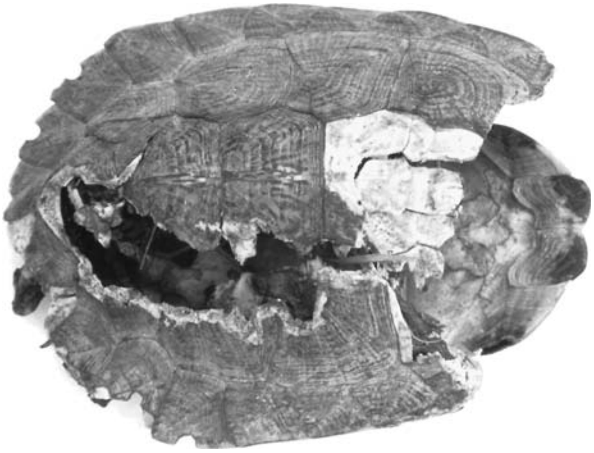

Fig. 2 – Adult male *Glyptemys insculpta* with lethal injury sustained as a result of an impact with a disc mower blade. Specimen exhibits severe trauma (Level 3) in all four quadrants and thus represents a Carapace Mutilation Index of 1.00.

The remaining mortalities (1 male and 2 juveniles) resulted from *G. insculpta* being buried alive. One juvenile was trapped by the collapse of a riverbank in June 1998. Its carcass was unearthed approximately 21 days later in an advanced state of decay. Another juvenile was buried in August 1999 when gravel from the riverbed was bulldozed up onto the banks in an effort to stabilize them. It was unearthed, still alive, approximately 25 days later from beneath 46 cm of gravel and tangled limb branches. Since this turtle would not have escaped without human intervention, it is considered dead for the purpose of this study. Finally, a male was buried in June 2000 beneath 40 cm of hard packed sandy loam when a new landowner ploughed a 30 ha cattle pasture in order to seed corn; its carcass was unearthed approximately 36 days later.

No mortalities were observed along roads or the railroad track. In addition, no turtles were known to have been killed by cattle; in fact, one adult male *G. insculpta* survived a stampede of approximately two dozen cows and calves completely unscathed. There was no evidence of commercial poaching at this site.

The recorded mortalities enabled us to compute estimates of survivorship and mortality from the sample population.

Table 1 – Most parsimonious survivorship models based on monthly known fate data for *Glyptemys insculpta* in 1998 ($n = 22$) and 1999 ($n = 28$) at an agri-forest site in southern Québec, Canada

Year	Model	AIC$_c$	Δ_i	w_i	K_i	Deviance
1998	{S(.)}	21.09	0.00	0.61	1	7.88
	{S(g)}	22.03	0.94	0.38	2	6.72
1999	{S(.)}	31.19	0.00	0.69	1	7.58
	{S(g)}	32.84	1.65	0.30	2	7.17

Notation follows that of Anderson et al. (2000): (.) = constant across months; (g) = group-dependant; AIC$_c$ = Akaike Information Criterion, second order; Δ_i = AIC$_c$ differences; w_i = Akaike weight; K_i = parameter number.

The most parsimonious survivorship model for our radio-telemetry data in both 1998 and 1999 was the constant monthly survival model $\widehat{S}(.)$ (Table 1). This model, however, did not have unequivocally strong support in either year, based on the w_i values. The group effect model $\widehat{S}(g)$ was the second most supported model in both years. Consequently, weighted averages of monthly survivorship for both models were calculated. The weighted average monthly survivorship for adults and juveniles in 1998 were 0.98 and 0.96 month^{-1}, respectively (Table 2A). In 1999, the weighted average monthly survivorship for adults and juveniles were 0.98 month^{-1} and 0.97 month^{-1}, respectively (Table 2B). As no mortalities occurred from October through May in either year, survivorship for that period was 1.00. Consequently, annual survivorship for adults in 1998 was 0.90; whereas, it was 0.81 for juveniles. For 1999, annual survivorship was 0.87 for adults and 0.83 for juveniles. Finally, annual mortality rates $(1 - S)$ were derived from the weighted average annual survivorship values. Adult and juvenile mortality estimates for 1998 were 0.10 and 0.18, respectively. Similarly, for 1999 these values were 0.13 and 0.17, respectively.

3.4. *Injuries*

Mutilation rates were higher in 1998 and 1999 than they were in 1995 for both sexes (Table 3). Adult mutilation rates were 90 ± 3% in 1998 and 1999. The mutilation rate of juveniles did not differ significantly between years. Ten of the 33 turtles (30.3%) captured in 1995 had sustained additional injuries to the carapace by the end of 1999. Of the 20 turtles captured in both 1998 and 1999, 40% ($n = 8$) sustained carapace injuries during that period. The frequencies of carapace and plastron injuries were higher in 1998 and 1999 than for 1995 (Table 4). Twelve percent (4 males, 3 females, and 1 juvenile) of the 66

Table 2 – Monthly survivorship ($\widehat{S}$) estimates for (A) 22 *Glyptemys insculpta* (18 adults and 4 juveniles) tracked via radio-telemetry from May to September 1998 and (B) 28 *G. insculpta* (22 adults and 6 juveniles) tracked via radio-telemetry from March to September 1999 at an agri-forest site in Québec, Canada

Model	Group	$\widehat{S}$	SE	95% CI	
				Upper	Lower
(A)					
{S(.)}	–	0.98	0.02	0.91	0.99
{S(g)}	Adults	0.99	0.01	0.91	1.00
	Juveniles	0.93	0.06	0.65	0.99
Model averaging	Adults	0.98	0.01	0.91	1.00
	Juveniles	0.96	0.03	0.74	0.99
(B)					
{S(.)}	–	0.98	0.01	0.94	0.99
{S(g)}	Adults	0.98	0.01	0.93	1.00
	Juveniles	0.96	0.04	0.77	0.99
Model averaging	Adults	0.98	0.01	0.94	0.99
	Juveniles	0.97	0.02	0.88	0.99

(.) = constant across months; (g) = group-dependent.

Table 3 – Intersexual differences in mutilation rates of *Glyptemys insculpta* inhabiting an agri-forest landscape in Québec, Canada

	Male		Female		Juvenile		Total	
	n	%	*n*	%	*n*	%	*n*	%
1995[a]	16	81.2	13	69.2	4	50.0	33	72.7
1998	10	90.0	11	90.9	2	50.0	23	86.9
1999	15	93.3	16	87.5	7	57.1	38	84.2

[a] Data from Saumure and Bider (1998).

Table 4 – Injuries to the shell, limbs, and tail of *Glyptemys insculpta* inhabiting an agri-forest landscape in Québec, Canada

Year	Sample size	Carapace		Plastron		Limbs		Tail	
		n	%	*n*	%	*n*	%	*n*	%
1995[a]	33	17	51.5	7	21.2	5	15.2	18	54.5
1998	23	15	65.2	6	26.1	4	17.4	14	60.9
1999	38	26	68.4	11	28.9	6	15.8	21	55.3

a Data from Saumure and Bider (1998).

G. insculpta marked at this site since 1995 had limb amputations. Six additional turtles had minor injuries consisting of missing claws or phalanges, for an overall limb mutilation rate of 21.2%. Only two turtles with limb amputations were captured in 1998–1999. Both were recaptures from 1995 and neither appeared to have impaired mobility, although the male, missing a right foreleg, was killed by a disc mower in 1999. Interestingly, seven of the eight turtles (87.5%) had right limbs amputated and no turtle had more than one limb amputated.

Mean Carapace Mutilation Index values for mutilated males ($n = 22$), females ($n = 29$), and juveniles ($n = 15$) were 0.20, 0.14, and 0.07, respectively. Based on the Carapace Mutilation Index values, severity of carapace injuries differed only between males and juveniles ($U = 7.04$, df = 1, $P = 0.008$). Analysis of Carapace Mutilation Index data for adults with levels 2 and 3 trauma revealed that significantly more adults were injured on the right side of the carapace ($Z = -2.561$, $P = 0.010$). A definite trend was detected in the distribution of injuries between the anterior and posterior of the carapace ($Z = -1.874$, $P = 0.061$).

Based on our examination of agricultural machinery, we were able to attribute certain carapace injuries to specific devices. Level 1 injuries to marginal scutes were consistent with impacts from the tines of tedders. Similarly, narrow level 2 gouges were also most likely the result of encounters with tedders. Level 2 fractures to the marginal scutes could be produced by either disc mowers or tedders. Severe level 3 fractures and clefts were most likely the result of sub-lethal impacts from the blades of disc mowers (Fig. 2).

4. Discussion

4.1. Survivorship

Long-term studies show that turtle populations are most sensitive to decreases in adult survivorship (Brooks et al., 1991; Congdon et al., 1993, 1994; Heppell, 1998). Moreover, chronic reductions in adult survivorship require increases in the already high juvenile survivorship in order to maintain population stability (Congdon et al., 1993, 1994). However, turtles appear to lack such a density-dependent response (Brooks et al., 1991). Regardless, compensatory changes in juvenile survivorship at our site seem unlikely, given the anthropogenic nature of the mortalities. Harding and Bloomer (1979) first speculated that increases in anthropogenic mortality of adult *G. insculpta* would result in population declines. At the time, however, it was believed that *G. insculpta* populations could maintain themselves in agricultural areas and public lands. Evidence now suggests that the non-commercial removal of *G. insculpta* by outdoor enthusiasts (e.g., fishermen and hikers) can result in local extinction within 10 years (Garber and Burger, 1995). Furthermore, Compton's (1999) sensitivity analyses showed that the harvest of two or three specimens annually from a population of 100 *G. insculpta* led to population extinction in 76 and 50 years, respectively. Mortalities at this site clearly are occurring at a rate that makes the population unsustainable, as one in five turtles were killed within a 2-year period. Both Brooks et al. (1991) and Heppell (1998) stressed that new sources of anthropogenic mortality in vulnerable life stages result in a much greater likelihood of extirpation. We conclude that agricultural activities at our site reduced survivorship of adults by 10–13% and of juveniles by as much as 18%. Such survivorship values support the contention that 23% fewer juveniles and 40% fewer adults in the 20+ age class compared to a forest population is indicative of a population decline (Saumure and Bider, 1998). Without some form of intervention, this population will continue to decline, collapse (i.e., “ghost population” *sensu* Compton, 1999) and eventually be extirpated. More recent data support this contention; the adult population size estimate was halved from 1995 to 2002 (Daigle and Jutras, 2005).

None of the mortalities we recorded were the result of natural causes (i.e., predation, disease, and senescence). Consequently, survivorship in an agricultural landscape over a 2-year period was 1.00 during periods of agricultural inactivity. This finding is consistent with the results of previous studies on *G. insculpta* that have reported very low natural (e.g., predation) mortality of 0.95–5.2% over three to nine years (Farrell and Graham, 1991; Brooks et al., 1992; Foscarini, 1994; Garber and Burger, 1995; Compton, 1999; Walde et al., 2003).

An analysis of our sex ratio data sheds further light on *G. insculpta* survivorship. Daigle (1997) documented a male: female sex ratio of 0.83:1 for the 52 wood turtles captured at this site in 1995. The 1998–1999 sex ratio for the 42 adults captured remains identical.

4.2. Agricultural machinery

Horse-powered mowing machines did not come into popular use until after 1840 (Danhof, 1972). Although sickle cutterbar mowers have been in use for approximately 200 years, rubber-tired tractors and complementary machinery only came into wide use during the 1930s. If this machinery had a negative effect on turtles, then populations would have been extirpated long ago. Disc mowers, however, were first introduced to the US from Europe in the mid-1970s (Rider and Barr, 1987). Fundamental differences exist between the cutting mechanisms of sickle cutterbar and disc mowers (Rider and Barr, 1987; Miller and Rotz, 1995). Specifically, sickle cutter-bars are characterized by a series of reciprocating blades that are protected from solid objects, such as stumps and rocks, by guards located along the cutterbar. In addition, the blades cut parallel to the ground at a relatively slow speed. Conversely, rotary disc mowers have two blades bolted to each of a series of discs that rotate at speeds of up to 283 km h^{-1}. Cutting height is adjusted by tilting the angle of the cutterbar downwards, which angles the rotating blades towards the soil. Field speed is only limited by the operator's ability to maneuver the machinery. The combination of angled blades, absence of blade guards, and high field and blade speeds in disc mowers, however, results in extensive trauma and death of adult *G. insculpta*.

Kaufmann (1992a) warned that crop rotations might have a negative impact on *G. insculpta*. Similarly, Dodd (2001) reported anecdotal evidence suggesting that many box turtles (*Terrapene* sp.) are killed each year by mowers. Bayley and Highfield (1996) warned that a change from traditional to mechanized ploughing techniques in Morocco would likely threaten aestivating Mediterranean spur-thighed tortoises (*Testudo graeca*). Hailey (2000) calculated that tortoise (*Testudo hermanni*) mortality resulting from ploughing and bulldozing was approximately 50% in affected areas of his site in northern Greece. The entombment and death of a *G. insculpta* in a pasture ploughed to cultivate corn provides the first concrete evidence that turtle populations also can incur losses from crop rotations and ploughs. In small populations, even the loss of a single adult turtle can seriously compromise the stability of the population as a whole (Congdon et al., 1993, 1994).

4.3. Injuries

Saumure and Bider (1998) observed numerous scrapes, gouges, and dents on carapaces of turtles at this agricultural site. They suspected that these shell injuries were the result of passenger vehicles, agricultural machinery, or cattle. We found that agricultural machinery (i.e., disc mowers, tedders, and rakes) was the source of injury. In addition, injuries were consistent with the mechanical action of tedders and rakes. Overall, agricultural machinery led to an increase of at least 11.5% in the frequency of mutilated turtles since 1995 (Table 3). This higher frequency was due to an increase in mutilation to both carapace and plastron (Table 4). Such data confirm that turtles continue to frequent fields during agricultural operations and that at least some survive encounters with machinery. Those adults that do survive encounters, however, do not do so unscathed. Future research should investigate the impact of mutilation on turtle growth, fecundity, and behavior (e.g., habitat selection).

The Carapace Mutilation Index did not detect any intersexual differences in the severity of carapace mutilations. As previously stated, no gender bias was expected based on turtle carapace height. We did detect, however, a significant difference between males and juveniles. Juveniles were not only less mutilated, but the severity of mutilations was significantly less as well. Harding (1985) reported that most *G. insculpta* are injured after attaining sexual maturity. Our data suggest that mutilation rates are a function of habitat use, exposure time, and turtle size. We suspect that the significantly lower shell profiles of juveniles contributed, at least in part, to the absence of trauma inflicted by disc mowers. Differences in habitat use between adults and juveniles also contributed (Tuttle and Carroll, 2003, 2005a,b, unpublished data). Alternatively, the incompletely ossified carapaces of juveniles may increase the probability of death (Moll and Legler, 1971; Wilbur, 1975; Magwene, 1999) and hence decrease the probability of encountering injured juveniles.

Levels 2 and 3 carapace injuries were not randomly distributed on *G. insculpta*. Adult turtles had significantly more injuries on the right side of the carapace (i.e., quadrants 2 and 4), with a definite trend towards the anterior (i.e., quadrants 1 and 2) (Fig. 1). Ernst (2001) reported that two *G. insculpta* had clefts in their carapaces, which he believed were inflicted by mowers. Both of his turtles were injured in quadrant 2 (Ernst, personal communication). As successive discs on a modular cutterbar rotate in opposite directions, one would expect a random distribution of carapace fractures based on the mechanical action of the machinery alone. The non-random distribution of carapace injuries may be influenced by specific turtle behaviors, traditional harvesting practices, and the type of mower used. First, *G. insculpta* actively select 'edge' habitats, including hayfield margins (e.g., Kaufmann, 1992a; Compton et al., 2002; Arvisais et al., 2004). Second, they have excellent hearing, comparable to that of a domestic cat, as measured by electrical potentials in response to sounds (Wever and Vernon, 1956). In addition, turtles have the ability to detect vibrations through their shells (Rosenberg, 1986). Thus, the approach of agricultural mowers should be detected easily. *Glyptemys insculpta* also are known to seek the safety of a river when danger is perceived (McCurdy, 1995; Saumure and Bider, 1998). Moreover, *G. insculpta* have well-developed spatial orientation and homing abilities (Tinklepaugh, 1932; Carroll and Ehrenfeld, 1978; Barzilay, 1980). Consequently, *G. insculpta* likely move directly towards the home river. Field margins are typically harvested first and, by tradition, at least one swath is cut around the perimeter of a hayfield in a counterclockwise direction (Rider and Barr, 1987, personal observation). Consequently, turtles fleeing field margins expose their right sides to mowers that are cutting counterclockwise along the river's edge. Only a disc mower set to a low cutting height can cause many of the mutilation patterns observed. Since the right side of the turtle faces the on-coming disc mower blades (Fig. 2), the direction in which the mower blades are rotating does not determine the side that is hit, as it would if a turtle was hit head-on. The preceding scenario is consistent with movement observations gathered from a distance via radio-telemetry during harvesting. Several turtles with large clefts previously inflicted by disc mowers, present in hayfields when harvesting commenced, successfully escaped to the river without further injury (personal observation). This suggests a learned response, particularly since those that were killed lacked severe carapace injuries prior to their deaths.

The limb injuries of *G. insculpta* have been attributed to predation from raccoons, *Procyon lotor* (Harding and Bloomer, 1979; Harding, 1985; Farrell and Graham, 1991; Foscarini, 1994). The present study supports the recent discovery that limb injuries also can occur as a result of encounters with agricultural mowers (Tuttle, 1996). Harding (1985) found that the recapture rate of turtles with amputated limbs was significantly lower than for intact turtles. This suggests that the long-term survival of *G. insculpta* with mutilated limbs is compromised. Only two of eight *G. insculpta* with mutilated limbs captured in 1995 were recaptured in 1998–1999. Whether the missing turtles emigrated, were subsequently killed, or died as a result of reduced mobility remains unknown. The two recaptured turtles, however, were followed via radio-telemetry during our 2-year study and had $S = 0.50$. We suggest that researchers with access to larger *G. insculpta* populations compare survivorship in turtles with different severity and number of limb amputations.

By excluding minor limb injuries (i.e., missing claws and phalanges), our amputation rate of 12% is consistent with the 9–13% recorded for other *G. insculpta* populations (Harding, 1985; Farrell and Graham, 1991; Foscarini, 1994; Tuttle, 1996; Walde et al., 2003). As with the distribution of carapace mutilation, limb amputations revealed a strong right-sided bias. These data provide additional support for the aforementioned hypothesis on the non-random distribution of carapace injuries.

4.4. *Erosion*

Although erosion is a natural process, the historical removal of most riparian woody vegetation along field edges clearly exacerbated the situation at our site. Grasses can only withstand about one third the sheer stress that well-developed root systems of woody vegetation can (Schmetterling et al., 2001). Bank erosion and subsequent attempts at stabilization accounted for the entombment of two of the five juvenile *G. insculpta* we tracked. Tuttle and Carroll (2005) tracked the movements of neonatal *G. insculpta* and found that they frequently moved to the herbaceous cover along hayfield banks. Since approximately 1.5 km of river was dredged and the banks ‘stabilized’, it is likely that other turtles were trapped also. As mentioned previously, Hailey (2000) reported that mechanical habitat destruction accounted for approximately 50% mortality of *T. hermanni* in affected habitats. Consequently, we believe that the paucity of juveniles documented at this site by Saumure and Bider (1998) can, at least in part, be attributed to juvenile mortality related to dredging operations and the frequent collapse of severely eroded banks.

4.5. *Management recommendations*

Garber and Burger (1995) attributed part of their population decline to the loss of reproductive female *G. insculpta*. Iverson (1991) believed that conservation efforts should be aimed at adult females. Indeed, sensitivity analyses for the desert tortoise (*Gopherus agassizii*) suggest that increasing the survivorship of large adult females can reverse population declines (Doak et al., 1994). Similarly, we believe that management strategies for the conservation of *G. insculpta* in agricultural landscapes should focus on increasing adult survivorship, as there does not appear to be any intersexual difference in mortality at our site. Frazer (1992) clearly outlined the futility of protecting nests, head-starting, and captive breeding if the sources of adult mortality are not addressed (Spinks et al., 2003). To that end, mortalities and injuries can be reduced greatly if hayfields are not cropped to within 25–51 mm of the soil. Biologists are criticized often for failing to address the socio-economic needs of private landowners (Warner and Brady, 1996). An immediate benefit to farmers is that raising cutting heights will reduce wear to the discs and knives (Rider and Barr, 1987). If blades are set to cut higher, mower blades and discs should last longer and easily pass over the carapaces of adult *G. insculpta*. Miller and Rotz (1995) recommended that forages be severed 50-100 mm above the soil. With limbs retracted, the maximum height of *G. insculpta* at our site was 82 mm; however, the species has been reported to attain a carapace height of 87 mm (Smith, 2002). Clearly, the implementation of the suggested 100 mm (4 in.) cutting height (Miller and Rotz, 1995) for fields within the range of *G. insculpta* would be beneficial. Realistically, however, landowners may not willingly adopt such a conservation measure because of the perceived loss of forage yield. We do not advocate that farmers schedule harvest times based on turtle movements nor do we advocate that agricultural areas be searched prior to mowing as suggested by some (Kaufmann, 1992a; Dodd, 2001). *Glyptemys insculpta* are difficult enough for researchers to locate in fields with the help of radio-telemetry equipment (personal observation). Fortunately, there exists a mutually beneficial solution. Agricultural research has shown that: (i) the lower portion of the forage stem has relatively little nutritive value, (ii) higher stubble promotes the retention of soil humidity, which results in increased yield in the subsequent harvest, and (iii) higher cropping reduces erosion as a result of runoff (Smith, 1978; Sharp et al., 1995). At our site, the turtles retreat to the river by the time of the second harvest. Therefore, farmers could crop down to 25 mm during the second harvest without jeopardizing turtles. Without even discussing the precarious status of a turtle, landowners can be shown that a small change in cutting height can increase annual yield and thus be profitable. Some landowners, however, are sympathetic to wildlife conservation. For these individuals, we would recommend that an unmoved buffer strip of at least 10 m be left on the perimeter of hayfields at the time of the first harvest (Bradbury and Kirby, 2006). Originally, this technique was suggested to create a nesting refuge and/or escape cover for birds, e.g., ducks (Labisky, 1957). It should reduce turtle-mower encounters as well. Despite the fact that ~300 m buffer zones have been recommended by several authors (Burke and Gibbons, 1995; Compton, 1999; Semlitsch and Bodie, 2003), we do not foresee their implementation on private agricultural lands without financial compensation (Cope et al., 2003). Although seemingly ideal, such a buffer zone would encompass every field at our site. Another technique that might prove beneficial would be to mow the part of the hayfield farthest from the river first. As the turtles naturally flee towards the river, this would provide a temporal buffer as well. While the risk of mortality because of machinery can be reduced, it cannot be eliminated altogether. Nevertheless, our study serves as an exemplar of where the objectives of endangered species conservation are not at odds with achieving agricultural production goals. We encourage farmers, land managers, and wildlife biologists to strive for such mutually beneficial solutions.

It should be noted that the indiscriminate destruction of fish habitat is a criminal offense in Québec. Consequently, the disturbance of riverbed aggregates could be stopped through legal action. Such action, however, does not solve the current erosion problem. We propose that a riparian zone restoration project based on multi-level community partnerships is the best solution. The use of soil bioengineering techniques can allow quick stabilization and the establishment of a long-lasting, native, riparian ecosystem (Isenhart et al., 1997; Lewis, 2002). The benefits of riparian vegetation and natural riverbanks over riprap type banks for fish are numerous (Schmetterling et al., 2001). In addition, fencing has been shown to ensure the quickest recovery of riparian zones (Holechek et al., 1982). Managers should, however, keep some natural erosion zones intact, since these areas are used by wood turtles for nesting. Although Québec law stipulates that it is legal for herds to ford and/or drink from water bodies, we recommend that streambank fencing be added, or reinforced, to prevent cattle from destroying new riparian vegetation and further eroding riverbanks (Hafner and Brittingham, 1993).

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