

Red flag for green spray: adverse trophic effects of *Bti* on breeding birds

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Summary

1. The expanding use of selective pest-control agents provides a unique opportunity to study food web interactions in the field while addressing major environmental issues. *Bacillus thuringiensis israelensis* (*Bti*) is the most commonly used microbial agent to control mosquitoes worldwide.

2. Using breeding house martins *Delichon urbicum* as a model species, we assessed the effect of *Bti* spraying on foraging rates and chick diet prior to and during 3 years of *Bti* spraying in the Camargue, France. Some 9051 feeding flights and 14 857 prey items were recorded in the early, mid and late nesting season at up to three control and three treated sites. Breeding parameters were assessed during 1 year at two control and two treated sites.

3. Intake of Nematocera (Diptera sub-order including midges and mosquitoes) and their predators (spiders and dragonflies) decreased significantly at treated sites, concurrently with increase of flying ant intake. Small prey (< 2.5 mm) were significantly more taken at treated sites, and large prey (> 7.5 mm) at control sites, with lower foraging rates at treated sites.

4. Clutch size and fledgling survival were significantly lower at treated sites relative to control with respectively 2.3 vs. 3.2 chicks produced per nest. Breeding success was positively correlated with intake of Nematocera and their predators at the nest level.

5. No previous study has provided compelling evidence of *Bti* affecting vertebrate populations following the suppression of prey species. Indirect effects caused by repeated application of *Bti* through food web interactions warrant more attention.

6. *Synthesis and applications.* *Bti* is considered the most selective and least toxic agent currently available to control mosquitoes. Mosquito-control programmes should integrate non-biased awareness campaigns and mitigation measures balancing the social demands for mosquito reduction with the factors involved in mosquito proliferation and dispersion. Such measures could consist in improved wetland management; reduction in areas and periods of *Bti* spraying; consideration of alternatives to *Bti* spraying, such as mosquito traps; specific measures to reinforce animal populations affected by *Bti*; and suspension of mosquito control in environmentally sensitive areas where nature preservation is a priority.

Key-words: *Bacillus thuringiensis israelensis*, bird breeding success, cascading effect, *Delichon urbicum*, diet assessment, food web perturbation, mosquito control, pesticide impact, trophic interactions

Introduction

As the demonstration of its specific acute toxicity to mosquitoes and black flies (Goldberg & Margalit 1977), *Bacillus thuringiensis* var. *israelensis*, serotype H14 (*Bti*) has become the most commonly used microbial insecticide to control these pest and vector species (Rowe, Margaritis & Wei 2008). *Bti* is con-

sidered non-toxic to humans, mammals, birds, fish, plants and most aquatic organisms (Boisvert & Boisvert 2000; Lacey & Merritt 2004). Significant effects on non-target fauna are largely limited to non-biting midges (Chironomidae) in laboratory experiments or field studies using dosages above recommended application rates (Boisvert & Boisvert 2000; Lacey & Merritt 2004). Studies addressing the indirect effects of *Bacillus thuringiensis* on breeding birds are scanty and showed no significant results (Hanowski *et al.* 1997; Holmes 1998; Sopuck, Ovaska & Whittington 2002). Nevertheless,

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owing to its selectivity, *Bti* is a good candidate to assess the effects of trophic-web perturbation on breeding birds that depends extensively on *Bti*-sensitive insects as a food source.

The Rhone Delta or Camargue in southern France is a mosaic of natural and human-modified ecosystems including agricultural fields (mostly rice), marshes, reed beds, temporary ponds, lagoons and salt pans spread over 145 000 ha. It is located within the biodiversity hotspot of the Mediterranean basin (Myers *et al.* 2000) and has over 1000 vascular plant and 400 bird species. To reduce the nuisance caused by biting mosquitoes to local populations and tourists, a control programme encompassing 2500 of the 25 000 ha of potential larval biotopes was investigated through impact studies on the non-target fauna by The Parc Naturel Régional de Camargue. Since August 2006, *Bti* spraying (aqueous solution of Vecto-Bac 12AS® at 2.5 L ha⁻¹) is systematically carried out, whenever *Ochlerotatus caspius*, *Oc. detritus* or *Aedes vexans* larvae appear in natural or semi-natural water bodies that are regularly monitored by technicians from the Entente Interdépartementale de la Démoustication (EID), a public service in charge of mosquito-control operations in France since 1965. Treated areas are located within a maximal distance of 8.5 km from the targeted zone, where mosquito nuisance is expected to be reduced by 90%. Frequency of *Bti* spraying depends upon meteorological conditions and water management, with approximately a third of mosquito production being related to human intervention on ecosystem hydrology. In any 1 year, the same water body may be sprayed more than once, depending on the monitoring results. For instance, 29, 46, and 41 aerial treatments representing a cumulative total of 3831, 5093 and 5282 ha were carried out in 2007, 2008 and 2009, respectively. These treatments refer to the area enclosing the sites of Salin-de-Giraud and Port Saint-Louis, as no information is currently available for the treated area of Pin de Fourcat (Table 1).

The house martin *Delichon urbicum* L. was selected as a model species for assessing the indirect impacts of *Bti* through the food web. This migratory aerial insectivore breeds colonially in human-inhabited areas. It feeds upon various arthropod species including Nematocera that are caught on the wing within 450 m from nesting site (Bryant 1973; Bryant & Turner 1982).

Materials and methods

Nestling diet was assessed at Sambuc (control) and Salin-de-Giraud (treated) sites in June 2006 before the first *Bti* treatments, and continued to 2009 with an equal number of control and treated sites increasing from 1 (2007) to 2 (2008) and 3 (2009). The colonies studied were at least 5 km distant from each other, located on houses within villages or large rural estates composed of several buildings and surrounded by both mosquito-producing aquatic habitats and agricultural land (Table 1). At each site, two faeces were collected from below ten nests, once in 2006 (mid-June) and once in each of three periods (early June, mid-June and early July) in 2007–2009, yielding 380 faecal samples and 14 857 prey items identified to order or sub-order. The two faecal samples were homogenized into one sample of which 50% was carefully scanned for prey sorting. Prey identification was based mainly on cuticular parts of heads. Prey digestibility varies among taxa (Jenni, Reutiman & Jenni-Eiermann 1990), but this bias was constant across sites. Prey size was estimated at 2.5- or 5-mm interval classes using a reference collection.

Foraging rates ($N = 9051$ observations) were assessed under rainless and windless conditions at all colonies by counting the number of flights that concluded with chick feeding from 18:00 to 20:00 h, a period during which foraging activity was shown to be high and constant in 2006 (B. Poulin & G. Lefebvre, unpublished data). Foraging rates were monitored during one afternoon at the same ten nests and three periods as those used for diet assessment from 2007 through 2009.

All the nests ($N = 68$) accessible from a ladder (≤ 8 m above-ground) at two control and two treated sites (Table 1) were checked twice a week from 11 May to 17 August 2009 using an endoscope (Ridgid Seesnake micro inspection camera with camera head of 9.5 mm diameter, Elyria, USA). The frequency of nest visits was a compromise between precision in estimation of breeding parameters and nest disturbance. We estimated laying date, clutch size, hatching success and number of fledglings (number of chicks alive on the last nest visit before fledgling) of all breeding attempts ($N = 105$).

STATISTICAL ANALYSES

Bti effects were estimated through Generalized Linear Models using a nested-design ANOVA. For diet comparisons, year, site and period were nested in treatment, and because nests were not necessarily occupied by the same individuals on consecutive years, this factor was nested in year. These analyses were performed on overall prey taxa and size, as well as individually for each prey taxa and size category. Foraging rates were compared using ANOVAS with year, period and site nested in treatment. Breeding parameters were normally distributed (Q-Q-plots) and compared using ANOVAS with sites nested in treatment.

Table 1. Situation and size of the house martin colonies studied in Camargue, France in 2009, giving the proportion of mosquito-producing habitat within a 400-m radius, as estimated by the Entente Interdépartementale de la démoustication (EID)

Colony sites	Situation	% Mosquito-producing habitat	Total no. of nests in 2009	No. of nests surveyed in 2009
Control				
Sambuc	Town	24	94	18
Saint-Andiol	Town + rural estate	35	78	0
Armellière	Rural estate	13	26	12
Treated				
Salin-de-Giraud	Town	19	130	14
Port Saint-Louis	Town	32	31	24
Pin Fourcat	Rural estate	28	59	0

When multiple tests were carried out, the P values were corrected according to the Holm-Bonferroni method (Holm 1979). The contribution of *Bti*-depressed prey to breeding success at the brood level was assessed with an all-effects Generalized Regression Model.

Results

Before the start of *Bti* treatments in 2006, prey taxa ($F_{(8,11)} = 2.43$, $P = 0.09$) and size ($F_{(6,13)} = 0.48$, $P = 0.81$) did not differ between the control and 'treated' site. From 2007, differences in diet were observed systematically between these two sites, as well as between any possible pairwise combination ($N = 15$) of one treated site and one control site sampled within a same year (ANOVAS, corrected $P < 0.02$). The probability of no difference in both prey size and taxa in 2006 is only $1/15 \times 1/15 = 0.004$. Overall, *Bti* treatments accounted for 58% and 63% of the variance observed in prey taxa ($F_{(9,311)} = 14.28$, $P < 0.0001$) and size ($F_{(6,314)} = 17.20$, $P < 0.0001$), respectively (Fig. 1). Nematocera, Araneae and Odonata were taken significantly more often at control sites, whereas Hymenoptera (flying ants) accounted for a larger portion of the diet at treated sites (Table 2). Flying ants were also a common prey at control sites, and their intake increased gradually over the nesting season ($F_{(2,177)} = 9.84$, $P < 0.0001$; $r = 0.998$, d.f. = 2, $P = 0.04$) to reach a peak during the fledging period in early July. This trend was not observed at treated sites ($F_{(2,177)} = 6.21$, $P = 0.002$; $r = 0.779$, d.f. = 2, $P = 0.431$), where ant intake reached a peak during the chick-rearing period in mid-June (Fig. 2). *Bti* treatments also affected prey size with more small prey (< 2.5 mm) taken at treated sites and more large prey (> 7.5 mm) taken at control sites (Table 2).

Foraging rates were influenced by *Bti* treatments ($F_{(1,350)} = 4.93$, $P = 0.027$) and periods ($F_{(1,350)} = 4.40$,

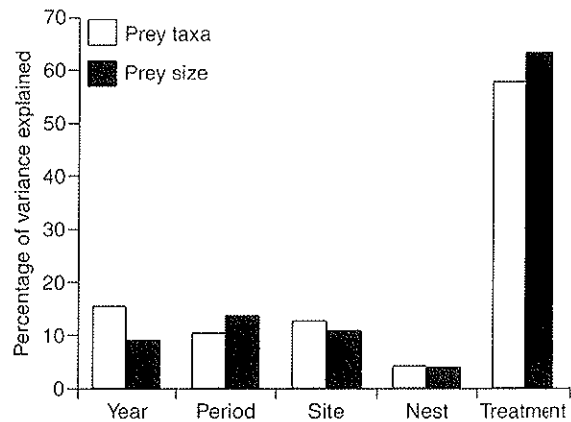


Fig. 1. Proportion of the variance explained by year, period, site, nest and *Bti* treatment on prey taxa and size found in faeces of nestlings from the colonies studied in 2007, 2008 and 2009. All variables significant (nested ANOVA, $P < 0.001$) except nest ($P > 0.29$).

$P = 0.002$), which accounted respectively for 41.2% and 36.8% of the variance observed between treated and control sites. Foraging rates were significantly lower at treated sites and during the fledging period at all sites (Fig. 3).

Mean laying date and hatching success of the first brood were similar at control (15 May, 80%) and treated (15 May, 75%) sites, but clutch size ($F_{(1,64)} = 8.48$, $P < 0.005$) and number of young fledged ($F_{(1,64)} = 15.03$, $P < 0.0002$) were smaller at treated sites (Fig. 4), with *Bti* treatment accounting for 99% of the variance observed relative to site. In spite of a larger proportion of second clutches at treated sites (40% vs. 63%), overall breeding success remained significantly lower ($F_{(1,64)} = 8.48$, $P < 0.005$) with 2.32 ± 0.21 (mean \pm SE) chicks fledged per nest on average at treated sites compared

Table 2. Diet of house martins in the Camargue at all sites studied from 2007 to 2009

Nestling diet	Control sites Mean \pm SE	Treated sites Mean \pm SE	$F_{(1,319)}$	P	Corrected P	% Variance
Prey taxa						
Hymenoptera (ants)	9.09 \pm 0.66	15.70 \pm 1.14	9.72	0.002	*	44.4
Coleoptera	11.54 \pm 0.54	9.49 \pm 0.56	0.20	0.660		1.7
Homoptera	0.96 \pm 0.09	0.89 \pm 0.12	1.86	0.170		11.6
Heteroptera	1.58 \pm 0.13	1.51 \pm 0.14	1.30	0.250		8.0
Hymenoptera (wasps)	2.10 \pm 0.18	2.70 \pm 0.30	6.02	0.015		26.1
Diptera (Nematocera)	15.25 \pm 1.46	5.04 \pm 0.55	22.93	< 0.0001	***	72.9
Diptera (others)	0.72 \pm 0.17	0.38 \pm 0.07	4.63	0.030		54.5
Odonata	0.94 \pm 0.05	0.27 \pm 0.03	72.97	< 0.0001	***	94.2
Araneae	0.46 \pm 0.08	0.10 \pm 0.03	8.65	0.003	*	58.2
Prey size						
0–2.5 mm	1.29 \pm 0.12	2.57 \pm 0.29	18.80	< 0.0001	***	49.1
2.5–5.0 mm	19.66 \pm 1.54	13.95 \pm 0.94	2.74	0.098		18.4
5.0–7.5 mm	14.35 \pm 0.96	15.73 \pm 1.03	0.06	0.810		0.5
7.5–10 mm	5.77 \pm 0.33	3.38 \pm 0.24	22.40	< 0.0001	***	81.7
10–15 mm	0.61 \pm 0.12	0.13 \pm 0.03	11.62	0.0007	***	53.6
> 15 mm	1.00 \pm 0.05	0.32 \pm 0.04	57.74	< 0.0001	***	92.8

Mean number of items per sample ($N = 380$) are provided for each prey taxa and size at the control and treated sites, with the proportion of variance explained by treatment relative to site, period, year and nest (nested ANOVA). Bonferroni-corrected values are * $P < 0.05$; *** $P < 0.001$.

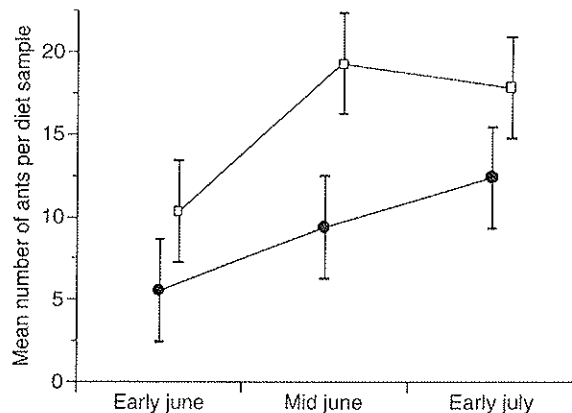


Fig. 2. Variation in the mean number ($\pm 95\%$ CI) of flying ants taken over the nesting period at control (filled circles) and treated (open squares) sites during the 3 years of Bti spraying.

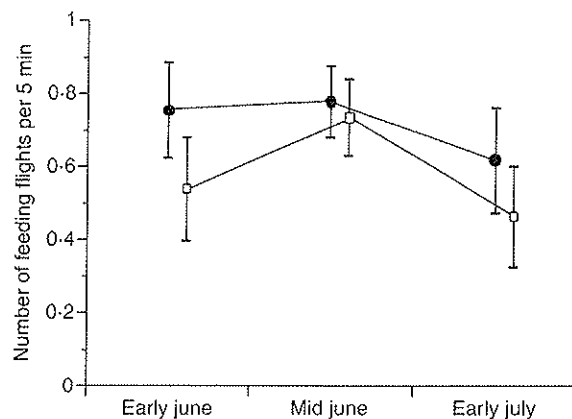


Fig. 3. Variation in mean foraging rates ($\pm 95\%$ CI) over the nesting period at control (filled circles) and treated (open squares) sites during the 3 years of Bti spraying.

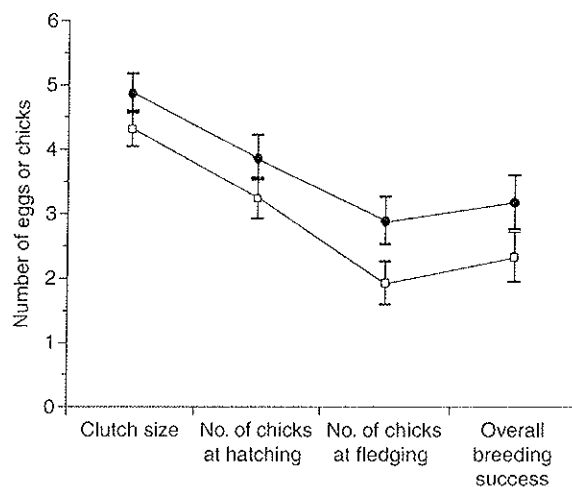


Fig. 4. Number of eggs and chicks from the first brood and the number of chicks produced from all breeding attempts at control (filled circles) and treated (open squares) sites in 2009. Data are means $\pm 95\%$ CI.

to 3.23 ± 0.92 chicks at control sites (Fig. 4). The intake of Nematocera, Araneae and Odonata was correlated with overall breeding success at the brood level across all sites ($R = 0.518$; d.f. = 3, 36; $P < 0.01$); and at control sites alone ($R = 0.683$; d.f. = 3, 16; $P < 0.05$).

Discussion

The breeding biology and foraging ecology of swallows and of house martins, in particular, is well studied (Bryant 1975, 1978, 1979; Bryant & Gardiner 1979). The breeding success of these short-lived species is largely influenced by food abundance and foraging conditions that are affected by weather (Bryant & Westerterp 1983; Turner 1983b). Food selection is mostly related to prey size, with larger prey being more energetically profitable (Bryant 1973; Turner 1982; Quinney & Ankney 1985).

In our study, the lower intake of Nematocera at treated sites is presumably related to a locally lower abundance of these Bti-sensitive insects. Because Odonata and Araneae are favourite prey of swallows' nestlings (Foelix 1996; McCarty & Winkler 1999), and major predators of Nematocera (Foelix 1996; Corbet 1999), their lower intake at treated sites suggests an indirect effect of Bti treatments through the food web. The lower intake of Nematocera at treated sites was mostly compensated by a higher intake of flying ants, an insect prey unrelated to aquatic ecosystems. Considering that the amount of food (bolus) per foraging trip is relatively constant in house martins and that foraging distance is inversely correlated with insect abundance (Bryant & Turner 1982), the lower foraging rates observed at treated sites suggests lower food availability, with ants acting as a substitute for Nematocera rather than being a preferred prey by house martins. Flying ants are a regular food source for swallows, including house martins (Bryant 1973), but they are generally taken more by adults than nestlings (Turner 1983a), possibly because of their high chitin content (Redford & Dorea 1984). The increasing intake of flying ants at control sites over the nesting period may be associated with improved assimilation efficiency by growing chicks.

Clutch size in birds is considered a good indicator of a female's energy level, and is correlated with food abundance in swallows (Ward & Bryant 2006). Breeding activities of house martins often start a month after spring arrival, being triggered by food abundance (Bryant 1975). The synchronous nesting activities at all sites suggests that current food level allowed the initiation of breeding, but that scarcity of food at treated sites limited the number of eggs in the brood. The impacts were compounded during the chick-rearing period, when food demands are highest (Bryant 1979). The most likely explanation for the decreased fledging success at treated sites is chick starvation. None of the nests surveyed were perforated or partially destroyed by predators, and many chicks missing from broods were found dead below the nests. The higher proportion of second clutches at treated sites did not compensate for the lower reproductive success of the first brooding attempt. Female house martins that rear two broods within a nesting season survive less well

than single-brooded ones (Bryant 1979), suggesting that *Bti* spraying could also affect adult survival, although to a lesser extent than chick survival. Breeding parameters were estimated during a single year, but the correlation between house martin breeding success and the intake of Nematocera, Araneae and Odonata, which was consistently lower at treated sites throughout the study period, reinforced the link between *Bti* treatments and reproductive success.

The Camargue is characterized by highly variable rainfall within and between years, as well as variable hydrological regimes among managed wetlands (Chauvelon 2009). Yet the comparison of treated and control sites revealed a stronger effect of *Bti* spraying than year, site and period altogether on prey taxonomy and size. The effect of *Bti* on bird diet is probably enhanced by the relatively low arthropod diversity of human-occupied areas that in turn reduces the number of potential alternative prey (Borrvall, Ebenman & Jonsson 2001; Lacey & Merritt 2004). However, considering the major role of Nematocera in wetland food webs, at both larval and adult stages (Armitage, Cranston & Pinder 1994; Batzer & Wissinger 1996), *Bti* spraying could have similar impacts on other vertebrates who depend on wetland ecosystems. Laboratory-derived data are useful for determining the potential risks to non-target species, but *in situ* studies are necessary to examine the interactions among species and trophic levels (Blus & Henny 1997; Relyea & Hoverman 2006). Most field studies have failed to demonstrate short or long term effects of *Bti* on non-target species, but indirect effects have received little attention so far (reviewed in Boisvert & Boisvert 2000 and Lacey & Merritt 2004; but see Cabello de Alba 2002). The Camargue provides excellent experimental conditions for investigating indirect effects of *Bti* spraying with a globally high density of Nematocera, including sites that were not *Bti* sprayed, and a sustained reduction of mosquito density after the initiation of *Bti* spraying.

The detrimental effects of chemical insecticides on the environment and human health have led to the call for biological alternatives such as *B. thuringiensis*, which is increasingly used worldwide to control insects with 13 000 tons sprayed annually (Rowe, Margaritis & Wei 2008). The potential of *Bti* for persistence, proliferation and residual toxicity has recently been demonstrated (Tilquin *et al.* 2008). Our work suggests that widespread spraying with *Bti* can have substantial effects on the demography of insectivorous birds. Cascade effects caused by repeated application of *Bti* and other pesticides (Hart *et al.* 2006) warrant more attention. The expanding use of selective pest-control agents provides a unique opportunity for community ecologists to study food web interactions in the field while addressing major environmental issues related to ecosystem services and biodiversity (Knight *et al.* 2005).

Mosquito-control in response to a public demand for increased comfort also provides an opportunity for implementing an adjustive management approach that integrates the evolution of public values and preferences (Maris & Béchet 2010). A negative value can be ascribed to mosquitoes and a positive value to *Bti*-control if the latter is considered harmless to the non-target fauna. However, a demonstrated impact of *Bti*

showing the positive contribution of mosquitoes to local biodiversity could modify these values. It is therefore important to implement non-biased awareness campaigns about mosquito-control effects and costs, and to adjust mosquito-control planning in the light of potentially changing values given to biodiversity.

Concluding remarks

Bti is considered the most selective and least toxic agent currently available to control mosquitoes. This study demonstrates that *Bti* applications at recommended rates, and applied to water bodies within 4 days of the appearance of mosquito larvae, have detectable effects at higher trophic levels, ultimately affecting vertebrate populations. Mosquito-control programmes should integrate the factors involved in mosquito proliferation (natural vs. anthropogenic), the dispersal probabilities of mosquitoes, the social demands for mosquito reduction, and the preservation of sensitive areas and species. This could result in various mitigation measures such as: (i) modification of wetland management to limit mosquito proliferation, especially under hydrological conditions that do not benefit the non-target fauna or stakeholders; (ii) improved drainage in urban and semi-urban areas to counteract unintentional practices that favour mosquito proliferation; (iii) selection of the mosquito-controlled area as a trade off between the acceptable degree of nuisance in the target zone and the environmental impacts in the surrounding treated habitats; (iv) potential limitation in the periods of mosquito control taking into account the energetic demands of the non-target fauna and the socio-economic pressure for mosquito reduction, as they both vary over time and are not necessarily synchronous; (v) consideration of alternatives to *Bti* spraying, such as mosquito traps, which target the area of mosquito nuisance (< 0.4 ha) rather than the area of mosquito production, with effects limited to biting insects (gravid females); (vi) specific measures to reinforce vulnerable animal populations affected by *Bti*: for swallows this could include the installation of artificial nests to favour breeding in Nematocera-rich non-treated areas; and (vii) suspension of mosquito control in environmentally sensitive areas where nature preservation is a priority and mosquitoes are not involved in transmission of human diseases.

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