INVASION OF THE HEMLOCK WOOLLY ADELGID ON EASTERN HEMLOCK IN THE GREAT SMOKY MOUNTAINS NATIONAL PARK

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ABSTRACT—Light to moderately-heavy hemlock woolly adelgid infestations on eastern hemlocks were discovered in the Great Smoky Mountains National Park in 2002. Mass releases of the biological control agent, *Sasajiscymnus tsugae*, were made initially at ten sites infested with the hemlock woolly adelgid. These sites were monitored through 2003 to assess the establishment of *S. tsugae*, the density of the adelgid population, and the impact on the health of eastern hemlocks. The average number of hemlock woolly adelgids at the study sites evaluated was 242 (85–412) on the terminal 25 cm of branches. The highest average number of hemlock woolly adelgids (412) from 10 samples per release tree occurred at the Laurel Falls 1 site and the lowest number (85) at the Gregory Ridge site. The average hemlock woolly adelgids per sample for infested trees 10 to 28 m from the release tree averaged 126 (0–478). Initial data indicate that tree transparency was negatively correlated to the increase in hemlock woolly adelgid population numbers. None of the sites sampled had average crown transparencies less than 50%. These data indicate this invasive pest was not established long enough at the time of this study to impact the overall health of sampled trees, but has since become well established. Released lady beetles were recovered at three sites in the fall of 2002. With the rapid spread of the hemlock woolly adelgid throughout the area, additional releases of the lady beetles were made to reduce populations of this invasive pest.

The exotic hemlock woolly adelgid, *Adelges tsugae* (Annand) (HWA), currently threatens to destroy the hemlock forests throughout the eastern United States (McClure, 1997). This exotic pest entered the United States from Japan in the 1920's and was first reported in Oregon on western hemlock, *Tsuga heterophylla* (Raf.) Sarg., in 1924. The exotic adelgid is believed to have been introduced from Asia on nursery stock of hemlocks (McClure and Cheah, 1999). Later, it was reported from Richmond, Virginia in the early 1950's (Stoetzel, 2002), in southeastern Pennsylvania in 1969, and in southern Connecticut in 1985. The adelgid has now spread throughout the eastern United States where it infests eastern hemlocks, *Tsuga canadensis* L., throughout its range. This pest is estimated to have damaged or killed over one-half of the eastern hemlocks in the forests in New Jersey and Virginia. Currently, the largest remnants of eastern hemlock in the world, which are presently confined to about 35,399 ha in the southern Appalachians, are in danger of being lost. The hemlocks are ecologically important, capable of reaching ages of 900 years and are a vital component of many old growth communities providing distinct micro-climates for a variety of wildlife ranging from arthropods to mammals. For example, several unique species that survive only in such habitats were catalogued among the 292 insect species reported associated with eastern hemlock (Buck et al., 2003; Buck, 2003). The survivability of these species will be dramatically impacted by the loss of this tree.

Several studies have been conducted on the life cycle and general development of the HWA. The basic life cycle of the adelgid is similar throughout its range (Gray and Salom, 1996; McClure, 1987, 1989, 1995*a*). This exotic adelgid is parthenogenetic, completing two generations annually on eastern hemlock. Some of the adults produced in May–June are winged individuals unable to reproduce on eastern hemlock. Many of these alates leave the host tree in search of spruce, the alternate host (McClure, 1989). Because no suitable spruce host is available in North America, they soon die. The wingless adults produced at this time can lay 50–300 eggs per female protected in a white, waxy covering (McClure, 1987). Upon hatching, the crawlers settle near the base of the needles where they insert their stylets into the xylem ray parenchyma cells and begin extracting sap. This feeding strategy suggests that saliva introduced during feeding produces a toxic effect significantly impacting the host plant (Young et al., 1995). Development in the southern Appalachians appears to be about one month earlier than for HWA populations in the northeastern United States (Grant et al., 2006). Crawlers that hatch in early July enter a non-feeding dormancy period until October–November when they resume feeding and develop throughout the winter producing first generation sisten eggs from February into late spring. Feeding activity results in discolored needles and premature needle loss, reduced new growth, branch die-back, and death of the infested tree within four to six years.

The vast and often rugged forest terrain wherein eastern hemlocks grow throughout the eastern United States as well as the density of trees and shrubs within forests prohibit the area-wide use of chemical insecticides to control this pest. Because no indigenous disease-causing organisms or native predators or parasitoids that can regulate this adelgid occur in the United States, mass releases of the lady beetles (*Sasajiscymnus tsugae* (Sasaji and McClure)) constitute the most commonly used tactic to suppress HWA populations (McClure, 1995*b*; Cheah and McClure, 1996). This beneficial predator has a similar biology and development time as the pest (Cheah and McClure, 1998). Although these biological control agents have been released against this pest, HWA has continued to spread throughout the range where eastern hemlocks grow.

With the discovery of the HWA at ten sites in the Great Smoky Mountains National Park (GRSM) in 2002, this exotic pest now threatens the aesthetic, economic, environmental and recreational values within the Park and region. This infestation is estimated to have been present at least two years prior to discovery. As a result, the United States National Park Service and United States Department of Agriculture Forest Service implemented a program to conduct mass releases of *S. tsugae* onto infested trees in 2002 within the GRSM in an effort to curtail the advancement and damage by the HWA (Lambdin and Grant, 2003*a*, 2003*b*). These coccinellids, which feed exclusively on HWA, were released onto infested hemlock trees at ten sites in the GRSM. Since the program began in 2002, more than 200,000 specimens of *S. tsugae* have been released. This project focuses specifically on the initial releases in 2002. Should they be capable of surviving and reproducing in the southern Appalachian region, it is anticipated that it will take 5–8 years for the predator populations to increase to levels where they can effectively suppress this established adelgid pest.

MATERIALS AND METHODS

Lady beetles were released onto HWA-infested trees at ten sites in the Great Smoky Mountains National Park between 1 June and 26 June 2002. Sampling was initiated on 15 September 2002 at five of the original ten release sites, and was subsequently expanded to include the original ten sites where mass releases of the lady beetle were made. Selected protocols developed by the New Jersey Department of Agriculture were used to assay hemlocks for beetle and HWA damage. Sampling was initiated at five sites in October–November, 2002 for HWA and lady beetles that included three Laurel Falls, Anthony Creek, and Gregory Ridge Trail sites and all 11 sites (ten release sites and a control site) were evaluated during the spring (April–May) and fall (October) of 2003.

Study Sites—Some 848 beetles were released at Laurel Falls site 1 [UTME264756, UTMN3951364] on 3 June 2002, 2,037 lady beetles at Laurel Falls site 2 [UTME264758, UTMN3951435] on 3 June 2002, 2,037 lady beetles at Laurel Falls site 3 [UTME264464, UTMN3951462] on 3 June 2002, 3,396 lady beetles at the Gregory Ridge site [UTME243106, UTMN3937325] on 25 June 2002, and 2,923 lady beetles were released at the Anthony Creek site [UMME251478, UTMN3940613] on 26 June 2002. All three Laurel Falls sites, located in the Gatlinburg region of the Park, are upland mixed forest sites, with the canopy dominated by eastern hemlock, red maple, and red and white oaks. The three Laurel Falls sites were sampled on 4 October, 7 October, and 18 October 2002. The Gregory Ridge site in the Cades Cove region is a middle elevation site dominated by eastern hemlock and American beech. The understory is primarily eastern hemlock, American holly, and American beech, and the site was evaluated on 1 November 2002. The Anthony Creek site is a lower to middle elevation site in the Cades Cove area dominated by eastern hemlock, red maple, and a few sourwoods. The understory is eastern hemlock and red maple, and the site was evaluated on 25 October 2002.

The Cataloochee Cove site [UTME310445, UTMN 3941668], located in North Carolina, was the most heavily infested site wherein 5,326 lady beetle specimens were released on 1 June 2002. Stony Branch [UTME242041, UTMN3945444] and Panther Creek [UTME229621, UTMN 3939493], both located in the Abrams area, received 3,953 and 2,998 beetles on 2 June and 3 June 2002, respectively. In the Wear Cove region, 3,118 beetles were released at Meigs Creek [UTME259816, UTMN3947858] on 25 June 2002. Also on 25 June 2002, 3,404 beetles were released at the Lynn Camp site [UTME261213, UTMN3942659], a middle elevation site located in the Tremont area. A control site without beetle releases located at Elkmont (UTME83350491, UTMN 35395638,) was selected (three trees) for comparison.

Sampling—At each site, the release tree (tree onto which lady beetles were released was designated as the "release tree") was used as the center of our plot and as our primary sample tree. The other trees sampled within the test sites were selected within 5 to 10 m, 11 to 17 m, and 18 to 28 m intervals radiating out from the release tree in the four cardinal directions (with up to 13 trees per site). These trees were marked with a numbered aluminum tag and flagging tape. For all trees, crown class (dominant, co-dominant, intermediate, or suppressed), DBH (diameter at breast height), crown ratio (measurement of the percentage of live foliage in the crown), and percentage of live branches were recorded. Trees also were evaluated for overall appearance including foliage color and amount of new foliage, and the crown condition was rated for general appearance and measured using the density and transparency (amount of light filtering through the foliage) scale provided by the New Jersey Department of Agriculture (Scudder et al., 2001). For infested trees, the degree (percentage) of tree infested by HWA was estimated. Sampling procedures consisted of counting the number of HWA from ten terminal branches 25 cm long monthly per site tree and four terminal branches 25 cm long monthly per sample tree radiating out from the site tree.

Indices were developed for the following tree conditions: crown class (1 = suppressed, 2 = intermediate, 3 = co-dominant, 4 = dominant), new foliage (based on percentage on tree: 0 = absent, 1 = <50%, 2 = >50%), foliage color (1 = dark green, 2 = not as dark green), crown appearance (0 = dead, 1 = poor, 2 = fair, 3 = good, 4 = healthy), crown condition (1 = thin, 2 = moderate, 3 = full), degree of HWA infestation (1 = absent, 2 = <25%, 3 = 25–50%, 4 = 50–75%, 5 = >75%), and prior HWA infestation (1 = no, 2 = yes). New foliage on infested trees was estimated as percentage of new branches with foliage in 2003. Beat sheets (91.4 cm^2 cloth fitted with dowel rods along opposing sides) were used to sample for lady beetles on the release trees and on the trees radiating out from the point of release at approximately 10 m, 17 m, and 28 m from the release tree. If trees were not accessible or if no acceptable tree was found, we recorded "no tree." However, if a tree was found, but had no adelgids present, then a zero was recorded and only the physical tree data were taken. Ten beat sheet samples from each release tree per site and four samples from trees surrounding the release tree were taken on each sampling date per site. Insect specimens that fell onto the sheet were collected, transferred to individual

TABLE 1. Comparison of crown ratio, live branches and new foliage per site, Great Smoky Mountains National Park, 2002–2003.

Site	% Crown ratio[a]	% Live branches	New foliage
Anthony Creek	85.26 abc[b]	87.29 ab	1.54 bc[c]
Cataloochee Cove	90.65 ab	81.70 abc	1.73 abc
Elkmont (Control)	93.33 a	88.57 a	1.81 ab
Gregory Ridge	85.43 abc	83.07 abc	1.34 cd
Laurel Falls 1	70.42 e	77.52 c	1.62 ab
Laurel Falls 2	76.60 d	77.77 c	1.52 bc
Laurel Falls 3	87.99 ab	78.25 c	1.63 abc
Lynn Camp	84.75 abcd	84.31 abc	1.08 d
Meigs Creek	85.35 abcd	78.94 bc	0.56 e
Panther Creek	77.33 cde	84.88 abc	1.58 abc
Stoney Branch	81.03 bcd	78.34 c	1.96 a

[a] Percent of live foliage in the crown of the tree.
[b] Numbers in a column followed by the same letter do not differ significantly.
[c] The index for new foliage was 0 = absent, 1 = <50%, 2 = >50%.

Ziploc® bags (900 ml), labeled (date, site, and tree number), and transported to the laboratory for identification and further analysis.

Data Analysis—The physical characteristics of each tree and the number of HWA per branch were recorded at each site on forms developed by the New Jersey Department of Agriculture. These data were entered into Excel® files and statistically analyzed using SAS (1999). Analysis of variance models were used to test for differences in means due to sites, years, and cardinal direction and distance from the site tree, as well as interactions among these factors. Least squares means were compared with Fisher's Least Significant Difference using a 5% significance level. Linear regression models were used to examine relationships among variables.

Results and Discussion

Both release and control sites were light to moderately-heavy infested at the time of predator releases. The average number of HWA per ten samples per release tree from the five initial sites was 242 (85–412) per 25 cm terminal branches. The highest average number of HWA (412) from these samples occurred at the Laurel Falls 1 site and the lowest number (85) at the Gregory Ridge site. The cumulative average HWA per sample for infested trees 10 to 28 m from the release tree was 126 (7–211) for the five sites. Samples from infested trees located 10 m from the release tree averaged 149 (0–478), those infested trees up to 17 m averaged 175 (0–442), and those up to 28 m averaged 42 (0–162) adelgids. This lower number for the latter was a result of either no adelgid infestation found on trees at 28 m east and west of the release tree within the five sites or no eastern hemlock tree was present in the area. For example, only one tree was found infested at 28 m from the release tree north and south at the Anthony Creek and Gregory Ridge sites, respectively. The average number of HWA per sample varied among sites for the two years. This trend continued for direction with higher numbers in 2002 compared to 2003.

The index denoting infestation density of HWA on eastern hemlocks at the 11 sites (including the control trees) was variable among sites. The average for all sites was 2.1 indicating about 25% of each tree sampled at each site was infested. While the population density of HWA was slightly higher on trees located south (2.21) of the release tree (2.20), no significant difference was noted for adelgid numbers on trees from the cardinal directions.

The crown ratio differed significantly ($F = 4.40$, $d.f. = 10$, $P < 0.0001$) among sites (Table 1). A significantly lower crown ratio was documented for infested trees at Laurel Falls site 1. The average crown ratio for the 11 sites was 83.5% (70.4–93.3). Only the Laurel Falls sites 1 and 2, Panther Creek, and Stoney Branch sites were significantly lower than the control site. Also, the crown ratio percentages were similar (81.4 and 82.4, respectively) for 2002 and 2003. However, factors other than HWA feeding such as elevation that influences temperature and water levels must be considered in assessing conditions of crown ratio, density and color (McClure and Cheah, 2002).

The percentage of live branches differed significantly ($F = 4.40$, $d.f. = 10$, $P < 0.0001$) among sites (Table 1). The lowest percentage occurred at the three Laurel Falls, Stoney Branch, and Meigs Creek sites, respectively. These sites differed significantly from the control site at Elkmont. The cumulative average was 81.9% (77.5–88.6) for the 11 sites. No significant differences were noted for direction regarding trees sampled at various distances north, east, south and west of the release tree. The percentage of live branches on the sample trees differed significantly in regard to specific distance from the release trees.

The indices for new foliage also differed significantly ($F = 4.40$, $d.f. = 10$, $P < 0.0001$) among sites (Table 1) and the initial five sites evaluated in 2002 had a higher index than those in 2003. The amount of new foliage was highest on trees at the Stoney Branch site and lowest at the Meigs Creek site. The Stoney Branch site was significantly different from five of the 11 sites. The Meigs Creek site differed significantly from all sites, while the Lynn Camp site differed from all sites except for the Gregory Ridge site. New foliage on trees at the Stoney

TABLE 2. Crown condition, appearance, density, and transparency at eleven sites in the Great Smoky Mountains National Park, 2002–2003.

Site	Crown condition[a]	Crown appearance	Crown density	Foliage transparency
Anthony Creek	1.71 bc[b]	3.32 bcd[c]	29.9 c[d]	62.3 abcd[e]
Cataloochee Cove	2.63 a	3.77 ab	37.8 ab	50.8 f
Elkmont (Control)	2.49 a	3.98 a	36.8 abc	57.1 cdef
Gregory Ridge	1.88 bc	3.46 abc	30.9 bc	67.5 a
Laurel Falls 1	1.79 bc	2.97 d	35.2 bc	66.3 ab
Laurel Falls 2	1.43 c	3.04 cd	34.6 bc	64.5 ab
Laurel Falls 3	1.67 bc	3.29 bcd	33.3 bc	63.3 abc
Lynn Camp	1.94 abc	3.10 cd	33.9 bc	64.7 abc
Meigs Creek	1.64 bc	3.40 abcd	35.8 bc	55.1 def
Panther Creek	1.79 bc	3.41 abcd	37.6 ab	54.3 ef
Stoney Branch	2.18 ab	3.52 abc	44.1 a	59.3 bcde

[a] Numbers in a column followed by the same letter do not differ significantly for condition ($F = 2.60$; *d.f.* = 10; $P < 0.006$), appearance ($F = 2.20$; *d.f.* = 10; $P < 0.02$), density ($F = 2.05$; *d.f.* = 10; $P = 0.03$), and transparency ($F = 3.47$; *d.f.* = 10; $P = 0.004$).

[b] Ratio of Crown condition (1 = thin, 2 = moderate, 3 = full).

[c] Foliage appearance ratio (1 = poor, 2 = fair, 3 = good, 4 = healthy).

[d] Foliage density as percent of canopy.

[e] Foliage transparency expressed as a percent of canopy without foliage.

Branch site exceeded that of the trees at the Elkmont control site. The average for all sites was 1.43 (0.56–1.96). The ratio for new foliage was lowest for the release trees (1.29) compared to those trees in the various directions of north (1.53), east (1.41), south (1.67), or west (1.54). No differences were noted for trees located at a specific distance from the release trees regardless of direction. However, the amount of new foliage differed between the years with a mean index of 1.63 in 2002 and 1.34 in 2003. These initial data may indicate that the decrease in new foliage is in part due to the presence of HWA populations on the trees, physiology of the tree, or to climatic differences between years.

The ratio for foliage color was lowest at the Laurel Falls site 3 (0.98) and Anthony Creek site (0.99), while the ratio for all other sites ranged from 1.03 to 1.19. Foliage color did not differ significantly for direction (north, east, south, west), for specific distances from the site tree, or between years evaluated. Crown condition (1 = thin, 2 = moderate, 3 = full) differed ($F = 2.60$, *d.f.* = 10, $P < 0.006$) among sites with the highest ratio for the Cataloochee Cove and Elkmont control sites and lowest for the Laurel Falls 2 site (Table 2). No differences were noted for direction, distance from the release tree, or year. The crown appearance of the trees differed significantly ($F = 2.20$, *d.f.* = 10, $P < 0.02$) among sites (Table 2) and for sample years. The control site at Elkmont had the highest ratio for appearance (3.98), while the lowest ratio was at the Laurel Falls 1 site (2.97). Appearance differed among years with the highest index of 3.58 in 2002 and only 3.19 in 2003. However, appearance may be the result of factors other than the presence of the HWA infestation.

Crown density was similar among sites ($F = 2.05$, *d.f.* = 10, $P = 0.03$) with the lowest rating occurring at the Anthony Creek site (29.9) and the highest rating at the Stoney Branch site (44.1) (Table 2). Crown density may indicate the degree of impact by the HWA on tree health as it will decrease as adelgid populations increase in size. The percentage for crown density of trees evaluated in 2002 (41.9) differed significantly to that recorded in 2003 (28.9). However, the lower crown density can not be fully attributed to the invasive pest as other abiotic and biotic factors were not evaluated. No significant differences ($F = 3.30$, *d.f.* = 4, $P > 0.01$) were noted for crown density at the four cardinal directions for the trees.

Foliage transparency ratings revealed significant ($F = 3.47$, *d.f.* = 10, $P < 0.004$) variation among the sites. These initial data indicate that tree transparency had a weak negative correlation ($r = 0.20$, $P = 0.20$) to the increase in HWA population numbers for 2003. Mayer et. al. (2002) suggest there is a threshold of about 60% where the mortality increases substantially. Transparency for all sites evaluated averaged 60.5% with the lowest at Cataloochee Cove (50.8%) and the highest at Gregory Ridge (67.5%) (Table 2). However, there was no significant mortality noted within the 10 release and the control sites. None of the sites had average crown transparencies <50%, which suggest the HWA had not been established long enough at the time of this study to significantly impact the overall health of sampled trees. No differences were noted for trees in any specific cardinal direction or distance from the release tree.

Only three adult *S. tsugae* were collected from beat sheet samples on adelgid-infested hemlock trees at Laurel Falls sites (2, 3) and one adult at the Anthony Ridge site. These beetles were collected on lower branches. No additional *S. tsugae* predators were found on trees beyond these release trees in the fall of 2002 or 2003. However, two specimens of the coccinellid, *Psyllobora vigintimaculata* (Say), which feeds on mold, were observed at the Laurel Falls 2 site, 28 specimens at the Anthony Creek site, and one specimen at the Gregory Ridge site. Also, an undetermined coccinellid was observed on HWA-infested terminal branches on trees at the Anthony Creek site. In addition, two specimens of the exotic lady beetle, *Harmonia axyridis* Pallas, were collected at Laurel Falls and Anthony Ridge sites. Additional assessments are needed to determine if either of the latter two species of coccinellids feed on HWA.

CONCLUSIONS

Although the exotic lady beetle was found only on three of the ten release trees, a low recovery rate has been commonly reported from studies in Connecticut, Pennsylvania, and New Jersey. For example, in a five-year assessment of two sites, the average number of lady beetles recovered ranged from 0.1 to 0.7 per tree at New Hartford and 0.1 to 0.5 at Bloomfield, Connecticut sites (Cheah and McClure, 2001). They found one beetle on a moderately infested tree about one-half mile from the release site. Low numbers for crown ratio, crown density, foliage transparency, and live branches are to be expected according to results reported by Cheah and McClure (2001). The low density readings are considered a result of the tree type (suppressed to intermediate) and would also affect the transparency. However, additional studies are necessary to determine if the health of the trees significantly improves as population numbers of the HWA diminish due to predation by the lady beetle. Mayer et. al. (2002) concluded from a monitoring program spanning 13 years that a cycle occurs where HWA populations will eventually crash after 5–6 years in non-predator release sites and the remaining trees begin to recover, but is followed by a subsequent increase in HWA numbers resulting in increased mortality to eastern hemlocks reaching 90% of the stands after 12 years of infestation.

The slight reduction in pest numbers on release trees after only two seasons may be due to a natural decline in the adelgid numbers due to environmental conditions, the biology of the pest, or possibly lady beetles feeding on the adelgids. Based on the amount of time from release, HWA density on the release trees, and recovery of predators, it does not appear that the reduced numbers of adelgids on the release trees at the various sites is a direct result of the release of predators at this time. With the subsequent releases of *S. tsugae*, more predators may be recovered in future surveys. Color appears to be useful as a means to obtain a general concept of the health of the tree from visual observations. Moderate to heavily-infested trees emit a grayish cast as opposed to a more green color of healthier trees.

The high crown ratios and transparency ratios for eastern hemlocks in the GRSM compared to data obtained in other regions (Mayer et. al., 2002) indicate the trees are still in relatively good health. Changes in the appearance and density of the host trees need to be consistently monitored over the next few years to understand the impact on the eastern hemlock and the density and spread of the HWA. Because a linear relationship exists between the degree of HWA infestation and crown transparency coupled with the threshold level of 60%, crown transparency may well be used as a means to assess the condition of the tree and potential mortality rates within the various habitats. It should also be noted that most studies conclude an increase in mortality as the crown ratio decreases. Because this project was initiated in the fall of 2002, more data are needed to determine if mass releases of *S. tsugae* will lead to their successful establishment within the area over time and effectively suppress HWA populations or if combinations of other exotic predators such as *Lariocobus nigrinus* Fender will be more effective against this pest. Also, biological studies are needed on this predator within the area to determine the most effective method of mass release of the lady beetles (adult or egg releases), their feeding and dispersal behavior within the region, and their impact on the pest populations. This project will provide basic information for future evaluation on the establishment and impact of *S. tsugae* on HWA populations.

In addition to the eminent problem to eastern hemlocks posed from the pernicious HWA, our discovery of another exotic pest, *Fiorinia externa* Ferris (elongate hemlock scale), denotes another significant threat to eastern hemlocks within the region. This pest has the potential to spread and cause further damage to eastern hemlock trees in the Park (Buck, 2003). This exotic pest has become a significant pest of eastern hemlock in several areas throughout the eastern United States, often co-existing with the HWA. Elongate hemlock scales are small, cryptic scale insects capable of inflicting substantial damage to the host tree resulting in loss of plant vigor, dieback, leaf drop, or eventual death. Because no studies have been conducted on this pest within the area, it is important that investigations on its biology, development, impact on hemlocks and potential biological control agents be initiated before substantial damage to this host tree is incurred. Protecting eastern hemlock stands is essential in maintaining the aesthetic, economic, and environmental integrity of the forests.

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