Tile Drainage Nitrate Concentrations in Response to Fertilizer Nitrogen Application

Kenneth D. Smiciklas and Aaron S. Moore
Department of Agriculture, Illinois State University, Normal, IL USA 61790-5020

Abstract: To elucidate the impact of the rate and timing of maize (Zea mays) fertilizer N practices upon surface water quality, a 14 ha field site was subdivided into six equal parcels of approximately 2.1 ha. Within each 2.1 ha parcel, 10.2 cm plastic drainage tile was installed on a 22.9 m grid with a single interceptor access point to collect tile drainage water on a weekly basis for nitrate-N (NO₃-N) concentration. The field site contained uniform soil (Strawn-Mayville-Birkbeck Association), with 2 to 4% slope, soil pH of 5.5 to 6 and organic matter content of 3 to 4%. Six agricultural fertilizer N practices for maize were evaluated; 196 kg ha⁻¹ fall-applied anhydrous ammonia with and without nitrapyrin (a commercially available nitrification inhibitor), 196 kg ha⁻¹ pre-plant spring anhydrous ammonia, 140 kg ha⁻¹ pre-plant spring anhydrous ammonia with nitrapyrin, 157 kg ha⁻¹ sidedressed (post-planting) anhydrous ammonia and zero-rate control. Soybean was grown during the 1997, 1999, 2001 and 2003 growing seasons. Maize was grown during the 1998, 2000, 2002 and 2004 growing seasons. In general, the application of a full rate of anhydrous ammonia in the spring produced equivalent grain yields to that of the fall-applied N treatments, with decreased NO₃-N release into tile drainage water. This reduction could be related to a tendency for increased plant N accumulation of the spring-applied N treatments and the shortened exposure time of the fertilizer N to loss. Based on the results from this study, producers within humid watersheds should apply N fertilizers in the spring before maize planting to minimize the loss of NO₃-N into tile drainage systems, while optimizing grain yield and productivity.

Keywords: Fertilizer timing and rate, field experimentation, maize, soybean

INTRODUCTION

Lake Bloomington is a major source of drinking water for residents of Bloomington, IL (USA) and has a history of nitrate-nitrogen (NO₃-N) concentrations that exceed 10 mg L⁻¹. The Lake Bloomington watershed consists of approximately 18,807 ha, of which 93.2% is used for agricultural purposes [primarily maize (Zea mays) and soybean (Glycine max) production], 2.5% is urbanized, 2.5% is wetlands and 1.8% is forested or contains surface water. The watershed is located within a humid continental climate (Köppen climate classification Dfa). The total population within the watershed is 4,600 residents. This watershed was selected for study because of its agricultural importance and location with the main maize production area within the United States of America.

Nitrogen fertilizers are necessary for profitable maize production, but there is concern that excessive rates of N fertilizer may have adverse effects on groundwater quality (Schepers et al., 1991). It has long been recognized that NO₃-N may leach beneath the rooting zone of maize and move into shallow groundwater supplies (Wagner et al., 1976). The application of N fertilizers (both synthetic and organic) in the production of row crops (especially maize on tiled drained land) can result in relatively high concentrations of NO₃-N in the surrounding surface waters (Keeney and DeLuca, 1993). Schilling and Libra (2000) found a direct linear relationship between NO₃-N concentration in surface waters and the percentage of land devoted to row crop agriculture within the watershed. Thus, agricultural applications of fertilizer N have been implicated in the leaching of NO₃-N from the soil into surface water sources.

There are other sources of NO₃-N in the watershed soil besides N fertilizer application. Non-agricultural sources of NO₃-N can include natural soil mineralization occurring primarily in the spring due to organic matter breakdown. Another source of NO₃-N in the soil can result from poorly maintained or inadequately-sized septic systems for rural residents (Gold et al., 1990). Thus, one must look at all sources of NO₃-N when determining the source(s) of NO₃-N contamination of surface water lakes.

Previous studies have indicated that the rate of N fertilizer was the primary determinant of the potential for NO₃-N leaching into groundwater when used in maize production (Patni and Cuttley, 1989), however other determinants governing leaching include weather conditions, soil conditions, and management practices.
conditions, soil types and crop management systems (Andraski et al., 2000). Work done by Baker and Johnson (1981) revealed that by controlling the amount, application timing and type of N fertilizer used can reduce overall NO$_3$-N concentration in tile drainage water. Methods of reducing the potential for N loss from intensive agricultural production systems, such as utilizing winter cover crops and lowering fertilizer rates, have been previously investigated by researchers (Staver and Brinsfield, 1990; Hubbard et al., 1991).

Intensive agricultural practices in United States attempt to maintain relatively high maize yield (12 to 14 Mg ha$^{-1}$) and are dependent upon N fertilizer applications. Producers within these regions may risk substantial economic loss from lowered productivity and grain yield without N fertilizer application (Roberts and Lighthall, 1991). Established agricultural production practices in these regions can result in excessive NO$_3$-N leaching by tile drainage into shallow groundwater supplies. Nitrogen fertilizer rates greater than 130 kg ha$^{-1}$ can easily be transported through clay loam soils under various precipitation amounts (Wagner et al., 1976). Hubbard et al. (1991) have shown that the majority of NO$_3$-N leaches beneath the root zone within 90 days of N fertilizer application if rainfall amounts to 20 cm in this time span. Seasonal patterns have also been observed to effect NO$_3$-N leaching, with more significant amounts occurring in the winter and spring periods when there is minimal plant utilization (Owens et al., 2000; Randall et al., 2003).

Therefore, one management practice that might reduce potential NO$_3$-N leaching would be to delay N fertilizer application until crop plants can effectively utilize the N. Although this practice has been shown to be effective in reducing NO$_3$-N leaching (Andraski et al., 2000; Baker and Johnson, 1981; Owens et al., 2000, Smiciklas and Moore, 1997), post-emergence N fertilizer applications (sidedressed) involves greater risk for the producer due to possible time delays caused by weather variability during this critical stage of crop development. Thus, a typical N fertilization practice in the United States is to apply fall N to minimize the risk of wet soils delaying N application after planting.

The objective of this study was to elucidate the influence of maize N fertilizer management upon NO$_3$-N concentration in water draining from agriculture tiles from a watershed within a humid climate. Specifically, six agricultural fertilizer N management techniques were utilized to determine the influence of fertilizer timing (pre-plant fall, pre-plant spring, or post-planting) and N rate (full, partial, or none) upon tile drainage nitrates in the context of a maize/soybean crop rotation. The use of a maize/soybean crop rotation mimics a common production practice in the watershed and will also elucidate the importance of crop species upon tile NO$_3$-N release. The knowledge gained from this study will aid in developing best management practices (BMPs) that promote the safe stewardship of row-cropped field sites in humid watershed climates.

**MATERIALS AND METHODS**

To elucidate the impact of maize fertilizer N practices upon NO$_3$-N release into water via tile drainage, a 14 ha site was selected within the Lake Bloomington watershed (Hoffman Farm, Hudson, IL, USA). The field site contained uniform soil (Strawn-Mayville-Birkbeck Association), with 2 to 4% slope, soil pH of 5.5 to 6 and organic matter content of 3 to 4%. The predominant soil series has been classified as a Rozetta silt loam (fine-silty, mixed, superactive, mesic Typic Hapludalfs). The soil is well-drained, with a saturated hydraulic conductivity of 4.23 to 14.11 mm sec$^{-1}$ (moderate permeability). An apparent seasonal high water table is at a depth of 1.22 to 1.83 m in some time between February and April in most years. Soil testing for plant-available NH$_4$ and NO$_3$-N was not performed due to the humid nature of the watershed climate. Plant-available NH$_4$ and NO$_3$ levels in the watershed soil vary due to the dynamic nature of the N cycle and are not predictive or stable in our humid climate (Ma and Dwyer, 1999).

The site was subdivided into six equal parcels of approximately 2.1 ha. A parcel size of 2.1 ha was selected to collect sufficient tile drainage water through the majority of the growing season for NO$_3$-N measurements to be taken, yet small enough to keep soil conditions uniform across the six parcels. Within each 2.1 ha parcel, 10.2 cm tile was installed on a 22.9 m grid with a single interceptor access point to collect water draining from the installed tiles on a weekly basis for NO$_3$-N concentration.

Six agricultural fertilizer N practices for maize were evaluated at this field site (Table 1). This research project was part of an educational effort to reduce the concentration of NO$_3$-N contained in the local water reservoir. Thus, the six treatments selected represented the vast majority of the N application techniques used by producers in the local watershed. All N applications utilizing anhydrous ammonia were applied using an N rate monitor to ensure accurate application of fertilizer. The fall-applied N fertilizer treatments were applied after the soil cooled to 10°C, in an effort to maximize longevity of the fall N treatments. The spring-applied treatments were applied two weeks prior to maize planting. The sidedressed N treatment was applied at the sixth maize leaf stage after crop emergence. No fertilizer N was applied to the zero rate control.
A maize/soybean rotation was employed at the site. The use of a maize/soybean crop rotation mimics a common production practice in the watershed. In addition, data collected during soybean production is an important step in the process of determining when (or if) NO₃-N leaks from maize N fertilization into tile drainage lines. Soybean was grown during the 1997, 1999, 2001 and 2003 growing seasons. Maize was grown during the 1998, 2000, 2002 and 2004 growing seasons. For maize, dry weight, nutrient content and nutrient concentration were estimated for each treatment as detailed by Smiciklas and Below (1992) when the plants reached physiological maturity. Six maize plants were removed from each treatment and then separated into leaves, stalks and grain. The total grain yield of each plot was measured by harvesting with a commercial combine and weighing the grain.

For the growing seasons that soybean was planted, all six field parcels were treated the same. Typical agronomic practices and equipment for conventionally-tilled soybean in the local watershed were utilized. Soybean was planted by the third week of May and averaged 450,000 plants ha⁻¹ in 19 cm crop rows. Pest control was conducted as needed by the local producer at the site. Crop harvest occurred in early October.

For the growing seasons that maize was planted, the crop was planted by the first week of May. Typical agronomic practices and equipment for conventionally-tilled maize in the local watershed were utilized. Maize averaged 80,000 plants ha⁻¹ in 76 cm crop rows. For maize, the six parcels were treated the same except for N fertilization timing and/or rate (Table 1). Pest control was conducted as needed by the local producer at the site. Crop harvest occurred in late September.

Given space and monetary constraints of the field experiment, no treatment replicates were conducted within a growing season. One reason no treatment replicates were conducted within the growing season was the educational focus of the experimental field site. The experimental field site was utilized as part of educational efforts to optimize fertilizer N application and maize yield for watershed producers. The six treatments selected represented most N fertilizer practices followed by producers within the watershed. A second reason was the limitation of uniform soil conditions and pre-existing drainage tiles. The 14 ha site that was selected was the largest, most uniform soil site within the watershed that had not been previously tile drained. To minimize potential experimental bias from a lack of treatment replication within a growing season, the plot size utilized in this experiment (2.1 ha) was many times greater than a typical agronomic experiment plot. Therefore, it is not appropriate to analyze the data with ANOVA techniques like the randomized complete block. Instead, the maize plant data was analyzed utilizing treatment means ± standard error. In addition, Student’s t statistic test comparing two samples with equal variance was calculated to compare 196 kg ha⁻¹ fall treatment versus 196 kg ha⁻¹ pre-plant spring treatment. This comparison was specifically designed to ascertain if spring-applied N is equivalent to fall-applied N for producers in the local watershed.

RESULTS AND DISCUSSION

The impact of the six maize fertilizer N practices upon NO₃-N leaching in tile drainage water was evaluated in a local watershed. The first year of this study provided a baseline to evaluate the uniformity of the six parcels of land before the application of fertilizer N treatments. Tile flow rates were measured during the 1997 growing season and no differences were found between the six treatments for water flow rates (data not shown). The 1997, 1999, 2001 and 2003 soybean yields for the six treatments were similar, with no significant differences among the treatments (data not shown).

For maize, the application of 196 kg N ha⁻¹ fall-applied N (as anhydrous ammonia) resulted in tile drainage water that contained 50% more NO₃-N, as compared to the same rate of anhydrous ammonia applied in the spring (Fig. 1, 2), similar to the work of Sanchez and Blackmer (1988). The 1998 and 1999 tile drainage NO₃-N data are representative of the trends observed since the inception of the field study. The addition of nitrapyrin (2-chloro-6-trichloromethyl-pyridine), a commercially-available nitrification inhibitor which delays NO₃-N conversion from NH₄-N to 196 kg N ha⁻¹ fall-applied N (anhydrous

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Table 1: Description of the six agricultural fertilizer N practices for maize utilized at the experimental site. The rates and timings selected represent the vast majority of N practices utilized by the producers within the local watershed.

<table>
<thead>
<tr>
<th>Field treatment code</th>
<th>N rate (kg ha⁻¹)</th>
<th>N application timing</th>
<th>N fertilizer material</th>
</tr>
</thead>
<tbody>
<tr>
<td>F3</td>
<td>0</td>
<td>None</td>
<td>None-zero rate control</td>
</tr>
<tr>
<td>F5</td>
<td>196</td>
<td>Fall</td>
<td>Anhydrous ammonia</td>
</tr>
<tr>
<td>F4</td>
<td>196</td>
<td>Fall</td>
<td>Anhydrous ammonia + nitrapyrin (compound that delays N conversion to NO₃-N)</td>
</tr>
<tr>
<td>F1</td>
<td>196</td>
<td>Spring</td>
<td>Anhydrous ammonia</td>
</tr>
<tr>
<td>F2</td>
<td>140</td>
<td>Spring</td>
<td>Anhydrous ammonia</td>
</tr>
<tr>
<td>F6</td>
<td>157</td>
<td>Summer</td>
<td>Anhydrous ammonia (sidebanded after planting)</td>
</tr>
</tbody>
</table>
Fig. 1: Measurements of weekly NO$_3$-N concentration from tile water taken from the six different N treatments for maize during the 1998 growing season (crop grown was maize). The treatment codes used in the figure are as follows:
- No N applied (F3)
- Fall-applied anhydrous ammonia at 196 kg N ha$^{-1}$ (F5)
- Fall-applied anhydrous ammonia + nitrapyrin at 196 kg N ha$^{-1}$ (F4)
- Spring-applied anhydrous ammonia at 196 kg N ha$^{-1}$ (F1)
- Spring-applied anhydrous ammonia + nitrapyrin at 140 kg N ha$^{-1}$ (F2)
- Summer-applied anhydrous ammonia at 157 kg N ha$^{-1}$ (F6)

Fig. 2: Measurements of weekly NO$_3$-N concentration from tile water taken from the six different N treatments applied to maize the previous year during the 1999 growing season (crop grown was soybean). The treatment codes used in the figure are as follows:
- No N applied (F3)
- Fall-applied anhydrous ammonia at 196 kg N ha$^{-1}$ (F5)
- Fall-applied anhydrous ammonia + nitrapyrin at 196 kg N ha$^{-1}$ (F4)
- Spring-applied anhydrous ammonia at 196 kg N ha$^{-1}$ (F1)
- Spring-applied anhydrous ammonia + nitrapyrin at 140 kg N ha$^{-1}$ (F2)
- Summer-applied anhydrous ammonia at 157 kg N ha$^{-1}$ (F6)
ammonia+nitrapyrin) decreased NO\textsubscript{3}-N concentration in tile water by only 10%, compared to the same rate of fertilizer N applied in the fall without nitrapyrin (Fig. 1, 2). Even with the use of nitrapyrin, fall-applied N losses (as measured by NO\textsubscript{3}-N concentration in tile drainage water) greatly exceed the recognized hazard level established by the United States Federal government of 10 mg L\textsuperscript{-1}.

In general, the two fall-applied N treatments (196 kg N ha\textsuperscript{-1} of anhydrous ammonia and anhydrous ammonia+nitrapyrin) had the highest overall NO\textsubscript{3}-N loss in tile drainage water (Fig. 1, 2), similar to the results of Randall and Vetsch (2005). The greater concentration of NO\textsubscript{3}-N release into tile drainage water even occurred during the growing season that soybean was grown, despite the fact that no fertilizer N was applied for soybean. In an effort to reduce NO\textsubscript{3}-N loss into tile drainage water, the spring-applied treatments investigated a reduction in N application rates. Spring-applied anhydrous ammonia rates included 140 kg N ha\textsuperscript{-1} (with the addition of nitrapyrin to conserve the applied fertilizer material as long as possible) versus a full rate of 196 kg N ha\textsuperscript{-1}. Despite a 30% reduction in applied N for the 140 kg N ha\textsuperscript{-1} treatment, the two spring-applied treatments reacted in a similar fashion for NO\textsubscript{3}-N release in tile drainage water (Fig. 1, 2). In contrast to the fall-applied treatments, the spring-applied treatments released less NO\textsubscript{3}-N into tile drainage water (Fig. 1, 2), similar to the results of Karlen et al. (1998). The application of anhydrous ammonia after maize planting (side dressing of 157 kg N ha\textsuperscript{-1}) also acted in a similar fashion to the spring-applied treatments in terms of NO\textsubscript{3}-N release in tile drainage water (Fig. 1, 2). As expected, the treatment with the lowest concentration of NO\textsubscript{3}-N release in tile drainage water was the zero rate control (no fertilizer N applied). Despite having the lowest NO\textsubscript{3}-N concentration of the six treatments, the zero rate control consistently exceeded the United States health standard for NO\textsubscript{3}-N concentration of drinking water of 10 mg L\textsuperscript{-1}. The data from the zero rate control plot indicates that the natural release of NO\textsubscript{3}-N from soil organic matter occurs to some degree during each growing season.

Despite increased NO\textsubscript{3}-N levels found in the tile drainage water, the fall-applied N treatments (196 kg N ha\textsuperscript{-1} of anhydrous ammonia and anhydrous ammonia+nitrapyrin) produced approximately the same maize grain yield as the 196 kg N ha\textsuperscript{-1} of anhydrous ammonia (Table 2). The full rate pre-plant spring application treatment contained similar plant N contents, as compared to the fall-applied treatment with nitrapyrin (Table 3). Overall, the application of anhydrous ammonia in the spring produced equivalent grain yields to that of the fall-applied treatments (p = 0.47; Student's t statistic), while reducing NO\textsubscript{3}-N release into tile drainage water. This reduction could be due to many factors, including the shortened exposure time of the fertilizer N to environmental losses and the increased plant N accumulation of the spring treatments.

Thus, one possible method to reduce NO\textsubscript{3}-N of water entering surface water lakes is to encourage the application of fertilizer N in the spring or after crop planting. Fall-applied N is lost at much greater rates than similar N fertilizer products applied in the spring. The addition of nitrapyrin to the fall N treatment did reduce NO\textsubscript{3}-N losses by 10%, although significant losses still occur in tile drainage water. Thus, fall application of N is not acceptable from an environmental standpoint. Pre-plant spring-applied fertilizer N reduces NO\textsubscript{3}-N loss into tile drainage water and produces similar grain yields.

### Table 2: Measurements of plant productivity for maize supplied with six fertilizer N treatments for four growing seasons

<table>
<thead>
<tr>
<th>Fertilizer treatment (field treatment code)</th>
<th>Grain yield (at 15.5%) (Mg ha\textsuperscript{-1})</th>
<th>Kernel weight (mg)</th>
<th>Kernel number (plant\textsuperscript{-1})</th>
<th>Harvest index (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No N applied (F3)</td>
<td>5.7±0.5</td>
<td>222±7.1</td>
<td>390±5.7</td>
<td>42±1.0</td>
</tr>
<tr>
<td>Fall-applied anhydrous ammonia at 196 kg N ha\textsuperscript{-1} (F5)</td>
<td>12.7±0.9</td>
<td>304±7.6</td>
<td>587±6.7</td>
<td>54±1.0</td>
</tr>
<tr>
<td>Fall-applied anhydrous ammonia + nitrapyrin at 196 kg N ha\textsuperscript{-1} (F4)</td>
<td>11.9±1.0</td>
<td>289±6.8</td>
<td>626±5.9</td>
<td>52±6.0</td>
</tr>
<tr>
<td>Spring-applied anhydrous ammonia at 196 kg N ha\textsuperscript{-1} (F1)</td>
<td>11.8±0.8</td>
<td>290±12.4</td>
<td>596±55.0</td>
<td>52±2.0</td>
</tr>
<tr>
<td>Spring-applied anhydrous ammonia + nitrapyrin at 140 kg N ha\textsuperscript{-1} (F2)</td>
<td>11.3±0.7</td>
<td>295±6.7</td>
<td>599±26.5</td>
<td>52±8±1.0</td>
</tr>
<tr>
<td>Summer-applied anhydrous ammonia at 157 kg N ha\textsuperscript{-1} (F6)</td>
<td>11.2±1.0</td>
<td>296±12.9</td>
<td>609±51.1</td>
<td>53±4±8.0</td>
</tr>
</tbody>
</table>

Values listed are the average±standard error for each treatment.

### Table 3: Measurements of plant N productivity for maize supplied with six N fertilizer treatments for four growing seasons

<table>
<thead>
<tr>
<th>Fertilizer treatment (field treatment code)</th>
<th>Reduced N (g plant\textsuperscript{-1})</th>
<th>NUE\textsuperscript{a} (g g\textsuperscript{-1})</th>
<th>N Utilization\textsuperscript{b} (g g\textsuperscript{-1})</th>
<th>N Uptake\textsuperscript{c} (g g\textsuperscript{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>No N applied (F3)</td>
<td>1.15±0.09</td>
<td>not applicable</td>
<td>59±6.7</td>
<td>not applicable</td>
</tr>
<tr>
<td>Fall-applied anhydrous ammonia at 196 kg N ha\textsuperscript{-1} (F5)</td>
<td>3.66±0.56</td>
<td>63±3±7.6</td>
<td>49±6.2</td>
<td>1.43±0.30</td>
</tr>
<tr>
<td>Fall-applied anhydrous ammonia + nitrapyrin at 196 kg N ha\textsuperscript{-1} (F4)</td>
<td>3.9±0.49</td>
<td>63±2±4.3</td>
<td>46±9.5</td>
<td>1.45±0.27</td>
</tr>
<tr>
<td>Spring-applied anhydrous ammonia at 196 kg N ha\textsuperscript{-1} (F1)</td>
<td>3.8±0.32</td>
<td>60±2±6.2</td>
<td>44±4.0</td>
<td>1.4±0.29</td>
</tr>
<tr>
<td>Spring-applied anhydrous ammonia + nitrapyrin at 140 kg N ha\textsuperscript{-1} (F2)</td>
<td>4.0±0.18</td>
<td>87±3±6.3</td>
<td>45±9.1</td>
<td>2.0±0.38</td>
</tr>
<tr>
<td>Summer-applied anhydrous ammonia at 157 kg N ha\textsuperscript{-1} (F6)</td>
<td>3.5±0.38</td>
<td>74±2±5.9</td>
<td>51±6.0</td>
<td>1.5±0.37</td>
</tr>
</tbody>
</table>

Values listed are the average±standard error for each treatment. \textsuperscript{a}NUE (nitrogen use efficiency) = grain weight per plant × amount of fertilizer N applied. \textsuperscript{b}N utilization = grain weight per plant × plant N content. \textsuperscript{c}N uptake = plant N content × amount of fertilizer N applied.
to the fall-applied treatments. However, pre-plant spring-applied N does involve an increased risk to the producer, since the spring season in the local watershed tends to be wetter, which may limit when the anhydrous ammonia fertilizer could be injected into the soil. With the wetter soils in the spring, soil compaction concerns also increase and a producer may have to choose between maize planting and N fertilizer application. The zero-rate control has the lowest NO₃-N loss into tile drainage water; however, unacceptable severe reductions in grain yield also occur. Thus, the best combination between producing grain and protecting the environment is the pre-plant spring applications of fertilizer N.

CONCLUSION

Six agricultural fertilizer N practices for maize were evaluated to determine if the timing or rate of fertilizer N application can reduce nitrate-nitrogen release into tile drainage water. In general, the application of anhydrous ammonia in the spring before planting produced equivalent grain yields to that of the fall-applied treatments, while reducing nitrate-nitrogen release into tile drainage water. This reduction could be due to many factors, one of which was the shortened exposure time of the fertilizer N to environmental losses. Another factor that may have contributed to this reduction is a trend for the pre-plant spring-applied anhydrous ammonia to have greater plant N accumulation. Thus, a feasible method to reduce nitrate-nitrogen of tile drainage water entering surface water lakes is to encourage the application of fertilizer N in the spring before crop planting. The knowledge gained from this study will aid in developing best management practices that deal with fertility and cultural practices that promote the safe stewardship of farmland in humid climates.

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