Risk assessment for rice planthopper and tungro disease outbreaks*

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Comparisons are drawn between the decision-making processes used in the management of two major pests of Asian rice production, namely, the brown planthopper (BPH) *Nilaparvata lugens*, and rice tungro virus disease (RTVD), which is transmitted primarily by green leafhoppers, *Nephotettix* spp. BPH exhibits quite different population dynamics and behaviour in the tropical and the temperate parts of its range, and this has important implications for its management. In the tropics, BPH is usually regarded as a secondary pest which becomes a problem only due to misuse of insecticides. Thus the risk of inadvertently inducing resurgence by the planthopper must be considered when attempting to control other rice pests. In temperate rice systems, the number of immigrants entering the crop and the temperature during the growing season are the main driving variables determining BPH population size. Here decisions can be made both in response to early warnings of planthopper immigration and in response to monitoring of populations during the cropping period. With RTVD (which occurs only in tropical systems), measures to prevent plant-to-plant spread of the disease within a crop are relatively ineffective. Early warning of the risk of tungro infection, however, would allow preventive measures to be taken such as the adjustment of planting times or the targeted deployment of resistant varieties.

Major changes in rice cultivation, such as the advent of large monocultures of high yielding rice varieties, increased cropping frequency and larger areas under irrigation, have had a dramatic effect on food grain production in Asia. Unmilled rice production has doubled from 240 million tons in 1966 to 480 million tons in 1993, although the harvested area has increased by only 13% (Hossain, 1994). Most of the growth in rice production has come, therefore, from increasing yields, rather than from increasing hectarage. Further increases in production are still needed, however, to meet a growing demand caused by continuing human population increase, thus further crop intensification seems inevitable. If future rice systems are to be both high-yielding and sustainable, an approach to crop protection which takes into account their complexities is needed to ensure efficient deployment of plant protection measures.

The abundance of the pests, the level of damage, and farming practices are determined by the ecology of the cropping system, the climate, the availability of pest control technology and the social, economic and institutional features of the locality (Norton et al., 1993). Pest management decision-making needs to take into account these various components. We focus here on two major rice pest problems: firstly, the brown planthopper (BPH), *Nilaparvata lugens*, which causes damage mainly by sucking the sap of the rice plant (although it also carries the virus diseases rice ragged stunt and rice grassy stunt), and secondly, rice tungro virus disease (RTVD) which is transmitted by the leafhoppers, *Nephotettix* spp. and, to a lesser extent, *Recilia dorsalis*.

Prior to the 1960s, BPH was only a minor pest in tropical Asia. The changes associated with the 'green revolution' of the 1960s and 70s led to an increase in the frequency and severity of outbreaks of this species such that it became one of the most serious pests of rice during this period (Dyck and Thomas, 1979). It is now thought that most BPH problems in the tropics are due to the overuse of some of the commoner insecticides (Gallagher, Kenmore and Sogawa, 1994; Greenland et al., 1994). Nevertheless, BPH is still causing major losses in the 1990s; in Thailand and Vietnam, for example, these were estimated at US$30 million in 1990/91 (Gallagher et al., 1994).

In contrast, in the temperate regions of east Asia (i.e. China north of the Tropic of Cancer, Korea and Japan) destructive outbreaks of BPH have been recorded intermittently for centuries. In recent years they have occurred with increasing frequency in many areas, and in China in 1991, rice losses caused by BPH together with the cost of control measures were estimated to have totalled US$400 million (Zhou, Wang and Cheng, 1995). Recent infestations north of the Yangtse River are a threat to the increased
Brown planthopper

Ecology

BPH is presumed to have originated in the tropics, as the species has no means of surviving the low temperatures, and the lack of its host plant, during winter in the temperate zone. Infestations of this species in temperate eastern Asia are initiated every year by wind-assisted long-distance migration starting from overwintering areas in the tropics and subtropics, and the species is thus able to colonise and exploit virtually all of the vast summer rice-growing area. The evidence for the migration and seasonal re-distribution of BPH (and of the White-backed Planthopper (WBPH), Sogatella furcifera, another rice pest) has been reviewed in detail by Kisimoto and Sogawa (1995). Although a few BPH can survive the winter in areas of China south of the 12°C average January isotherm, the major sources of migrants are thought to lie further south, below the 19°C January isotherm (possibly in northern Vietnam and the south of Hainan Island) where the planthoppers can breed all year round (Figure I). From these overwintering refuges, BPH spreads north- and northeasterwards every year, in a series of movements by successive generations which eventually take the species as far as northern China and across the sea to Japan (Figure I). The northward progress of the invading planthoppers is dependent on the advance of warm southwesternly winds, which in turn is related to the position of quasi-stationary seasonal weather fronts such as the Bai-u front.

The migrations of BPH from the Asian mainland to Japan entail over-water flights of distances of at least 750 km, or if the migrants originate in south-east China, over 1200 km. These movements can occur only under weather conditions which give rise to strong southwesternly or westerly winds across the East or South China Seas. In fact, the initial immigrations of BPH (and WBPH) in Japan are particularly associated with the presence of low-level jet (LLJ) winds: these form in the warm sectors of depressions which move along the Bai-u front in June and July (Watanabe et al., 1991; Watanabe, 1995). A computer programme has been developed to analyse weather data, and produce
'mesh maps' of estimated wind velocity from which LLJs and other planthopper-transporting winds can be monitored (Watanabe, 1995) (see Figure 2).

Circumstantial evidence existed of a series of 'return' migrations of BPH in a generally south-westward direction during the autumn, on the then prevailing northeast monsoon (Kisimoto and Sogawa, 1995), and these movements have recently been confirmed by radar observations in east central China in late September (Riley et al., 1991). After take-off in the late afternoon or at dusk, large numbers of migrating BPH flew for several hours during the evening, often in a dense layer (Figure 3). Movements further towards the south occur in late autumn (October) and it is quite possible that some descendants of individuals which invaded temperate areas at the beginning of the season, eventually return to the overwintering areas (Riley et al., 1995b). Whether the putative 'returnees' have any significant impact on BPH populations which remain within the tropics (e.g. in maintaining the proportion of the long-flying genotypes) is not clear.

These long-range migrations contrast strikingly with the limited movement of rice insects observed by radar during the dry season in the Philippines, where flight activity was very largely confined to periods of about 30 min at dusk and dawn (Riley, Reynolds and Farrow, 1987) (Figure 3). Other evidence from the Philippines also suggested that BPH movements were predominantly short-range (Perfect and Cook, 1994), and this is, perhaps, not surprising because in the humid tropics, rice (cultivated, ratoon or wild) is present all year round and movements over a few kilometres would be enough to ensure maintenance of the planthopper populations. In addition, long-fliers may be particularly uncommon on tropical islands far from continents because emigrants leaving the islands are unlikely to be replaced to any significant degree by long-flying immigrants from remote overseas sources.

However, recent aerial sampling studies in tropical areas of India (Riley et al., 1995a) indicate that moderately long-range movements by BPH occur there. Overall, we tentatively conclude that long-distance migration of BPH is most adaptive in temperate continental areas, moderately adaptive in tropical continental areas (especially those with a more pronounced dry season) and least adaptive in archipelagos (e.g. Philippines) or peninsulas (e.g. Malaysia) in the humid tropics.

As outlined above, in temperate areas of east Asia, long-range migration is a major factor leading to outbreaks of BPH and, moreover, the final population size is closely related to, and can be forecast from, the initial numbers of immigrants arriving and breeding in the paddy (Hirao, 1979). Typically, in temperate rice systems, the BPH population increases rapidly during the season through a series of synchronised generations (Figure 4a). In Japan, regression models are used to predict population density from densities earlier in the season (Kuno, 1984). Similarly, in the lower Yangtse area of China, simulation modelling (Cheng and Holt, 1990) showed the rate of immigration was the most important determinant of subsequent population density in the paddy. A second important factor here

Figure 3. Aerial density of insects at different heights during the late afternoon and evening, as detected by high-frequency radar (a) at Marsit, Laguna Province, Philippines (average for nine observational evenings in March 1984); and (b) at Jiangsu, near Nanjing, China on 28 September 1988. The brief dusk flight of rice insects in the Philippines contrasts markedly with the mass overflight of BPH, continuing for several hours, observed in China.

Figure 4a. Population growth in BPH in rice paddy in Kyushu, Japan (from Kusakabe, 1979)
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Dry season
1979

--- nymphs

--- adults

20 40 60 80 100

Days after transplanting

Wet season
1981

0.4

0.6

Number of N. lugens per hill (log(n+1))

Figure 4b. Population growth in BPH in rice paddy in Liliw, Philippines (modified from Cook and Perfect, 1989)

appeared to be temperature; cooler summers (July-August) and warmer autumns (September) were favourable for BPH.

Differences between tropical and temperate rice systems are largely due to seasonality. BPH cannot survive the winter in temperate areas, and populations of the planthopper's natural enemies also decline to very low densities at this time. At the beginning of the rice growing season, BPH populations (established by the initial immigrants) start to grow rapidly and the numbers of predators are apparently insufficient to prevent this increase (Cheng and Holt, 1990).

In tropical regions, on the other hand, predators and parasites have an important role in regulating BPH populations (Ooi, 1980; Kenmore et al., 1984; Benrey and Lamp, 1994), as long as broad-spectrum insecticides (which can cause serious mortality to such natural enemies) are not used (Chelliah and Heinrichs, 1980). On untreated rice, therefore, BPH outbreaks in the Philippines were found to be rare, even on susceptible varieties (Cook and Perfect, 1989). As might be expected in a situation where natural regulatory mechanisms determine population dynamics, immigration rates alone cannot be used to predict population growth in the Philippines (Cook and Perfect, 1985), and typically, BPH populations do not grow steadily during the course of the season (Figure 4b). Simulation modelling also supports the view that the level of immigration is generally of little use in predicting BPH population growth in tropical rice (Holt et al., 1989). Problems due to BPH migration may still occur in the tropics, however, if during an outbreak very large numbers of planthoppers move between asynchronously planted, contiguous cultivations. Modelling studies suggest that such short-range mass movements may enable the population to escape from the regulatory action of natural enemies in a particular field (Holt et al., 1989).

Management

The key importance of migration from distant sources in the population dynamics of BPH and WRPH in the temperate zone has led to the development of quite elaborate forecasting systems in the countries concerned. In China, for example, information is disseminated at a number of institutional levels (national, provincial, county, village and farmer) and over several time scales (long, medium and short-term) (Tang, Cheng and Norton, 1994; Zhou et al., 1995). Long-term forecasts based on population size in the source areas and historical data on population development give an indication of risk, and can play an important role by allowing decisions to be made early in the season, e.g. on choice of rice variety or on preparations for insecticide use. More specific information about population dynamics and the suitability of weather for migration are needed to make more definite predictions about the timing of immigrant arrival (Tang et al., 1994) (Figure 5). The use of a meteorological model to predict the timing and location of planthopper immigration into Japan has been mentioned above. The outputs from this model, along with pest survey data, form part of a national forecasting service for planthoppers and other rice pests provided by the Japanese Ministry of Agriculture (Watanabe, 1995).

Once immigrants begin to arrive, information from the field, including pest surveillance data, becomes important. A number of decision points can be identified during the season and Figure 6 summarises some of the information which can be used at each point. From this schema, an expert system has been developed which prescribes tactics for BPH management in the late paddy in Zhejiang Province (Holt, Cheng and Norton, 1990). It uses the opinions of experienced rice pest control practitioners and the results of simulation modelling to synthesise available information and produce a prognosis. The main aim was to provide a training tool for extension staff in order to increase the breadth of information used in the recommendations they provide.

The forecasting schemes used in temperate rice systems are less appropriate in the tropics. The main problem, the overuse of insecticides, has now been
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Time of application (days after transplanting)

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BPH population change: ++ large increase, + increase, 0 little effect, - decrease, -- large decrease.

Figure 7. Summary of the results of a simulation analysis (Holt et al., 1992) showing the relative magnitude of BPH population change predicted due to an insecticide application, according to compound specificity and application time.

Reduced through the actions of various agencies including the International Rice Research Institute (IRRI) and the United Nations Food and Agriculture Organisation (Matteson, Gallagher and Kenmore, 1994). It remains important, however, to minimise the risk of inadvertently creating BPH problems through attempts to control other rice pests with insecticides.

To consider this question, Holt, Wareing and Norton (1992) used a simulation model to assess the impact of insecticide applications applied at different times. The results are summarised in Figure 7. When the insecticide was assumed to be highly selective for planthoppers, and not to cause mortality to natural enemies, then applications between 30 and 45 DAT caused significant reductions in simulated peak numbers. Earlier sprays had less impact. Where the insecticide killed natural enemies but not planthoppers (which may well be the case with some compounds used against lepidopteran pests, for example), then some degree of resurgence usually occurred. A more unexpected finding was that where an insecticide caused mortality to both BPH and natural enemies, early sprays resulted in resurgence but later sprays achieved some level of control. The general conclusion, that it was particularly important to avoid early season insecticide use, was very robust to changes in model assumptions. This supports IRRI recommendations that sprays in the first 40 days of the crop should be avoided.

Rice tungro virus disease

Tungro is a composite disease caused by rice tungro spherical virus (RTSV) and rice tungro bacilliform virus (RTBV) (Cabauatan and Hibino, 1988). Both viruses are transmitted semi-persistently by a number of leafhopper (Cicadellidae) species, but principally by Nephotettix virescens. Severe leaf yellowing and stunted growth occur when a plant is infected with both viruses (Ou, 1985). Symptoms start to appear 1–2 weeks after infection. The use of vector-resistant rice varieties is the basis of the current approach to RIVD management but Dahal et al. (1990) showed that varieties do succumb to tungro once leafhopper populations have adapted to them.
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Epidemiology

A number of factors have been suggested as being related to the risk of tungro problems (Thresh and Chancellor, 1996). These include rice variety, planting data, cropping frequency, vector abundance and inoculum availability. Therefore, tungro risk in a particular field is only partly dependent on crop-specific factors such as the susceptibility of the variety grown. It is also determined by area-wide factors such as the proportion of susceptible varieties, the distribution of planting dates, and the age, position, number and potency of inoculum sources in the locality. A number of surveys have been carried out from which it has been possible to correlate tungro incidence with agro-ecological variables. In the highly asynchronous rice cropping system found in Bali, Indonesia, Suzuki et al. (1992) reported that tungro outbreaks were triggered by the sporadic occurrence of severely infected paddy fields in RTVD-endemic areas around the beginning of the wet season. In a regression analysis, Suzuki et al. (1995) found that almost 50% of the variation in the incidence of newly infected fields in a particular month was explained by three variables: new infections in the previous month (which are an important source of inoculum), occurrence of crops 2-3 months old (which are the major source of vectors), and rainfall in the present month.

Savary et al. (1993) analysed survey data collected from three sites in the Philippines, namely, Central Luzon (between 1973 and 1980) and North Cotabato and Sultan Kudarat (between 1983 and 1987). In a non-endemic area (Central Luzon), tungro outbreaks were mainly associated with the occurrence of infective vectors, and the size of the leafhopper population had less influence. In the two tungro endemic areas, increasing tungro incidence was also associated with a larger number of infective vectors but the size of the leafhopper population was also important. They concluded that inoculum, as measured by infective vectors, has a greater influence on tungro outbreaks in the non-endemic than in the endemic areas.

In a recent survey carried out in a tungro-prone locality of Southern Luzon in the Philippines, the association between tungro incidence and variety type, planting date, vector abundance and distribution of inoculum sources was investigated. The survey spanned 2 years, and here we summarise some of the findings from the first year (Chancellor, Tiongco and Holt, 1995).

There were significant differences in RTVD incidence related to month of planting (Figure 8). Some planting occurred in every month but the main planting periods were in December–January (dry season) and May–July (wet season). Crops planted late (in either season) suffered very much worse tungro problems than those planted earlier. Higher tungro incidence occurred in the wet season than in the dry and very large differences were present between the two variety groups. Although ‘field resistance’ is known to be based on resistance to the vector not the viruses, there was no significant difference in abundance of either adult or nymphal vector populations between the two groups. It appears from this that the resistance must be mediated in such a way that vector population size is not affected.

![Figure 8. Results of a survey of RTVD incidence (Chancellor et al., 1995), showing the proportion of plantings in each of five disease incidence categories (a = 0, b <1% infected, c <5%, d <10%, e >10%) from November 1992 to October 1993 on ‘field’ resistant and susceptible varieties. The classification of ‘field’ resistance was based on multi-location screening conducted by the Philippine Rice Research Institute, unpublished.](image)

![Figure 9. Results of a survey of RTVD incidence (Chancellor et al., 1995), showing the proportion of potential new infections (fields at a stage vulnerable to infection but not infected at the previous observation date) which became infected with RTVD, in relation to distance from the nearest source of inoculum (a field with >1% RTVD incidence at the previous observation date).](image)
Within variety groups, vector abundance made a significant contribution in regression models predicting incidence. Therefore, tungro incidence was significantly affected by leafhopper numbers. This is consistent with previous findings from some tungro-endemic areas (Suzuki et al., 1992; Savary et al., 1993). However, in other studies, tungro incidence was not always correlated with vector numbers (Bottenberg et al., 1990), and it was concluded that vector number might not be very important once tungro is already established in an area. Clearly, vectors are a necessary, but not sufficient condition, for disease spread. In our study in a tungro-prone area, inoculum availability is likely to be less of a constraint than is generally the case. Where low inoculum availability limits disease spread, high vector numbers may or may not be associated with a high tungro incidence. In such cases the impact of vectors may be less easy to detect.

The impact of proximity of inoculum sources was assessed by examining the occurrence of new infections in relation to their distance from the nearest inoculum source (Chancellor et al., 1995). A strong effect of source proximity was evident for both resistant and susceptible variety groups (Figure 9). The results suggested that if a field was more than 1 km from a disease source, the risk of RTVD would be low, even in a tungro-prone area. The view that inoculum transport is largely short-range also gains support from flight duration studies on (tethered) N. virescens which show that most individuals fly for only short periods, and are unlikely to travel far (R. J. Cooter, unpubl. results).

Management

Attempts have been made to curtail disease spread between plants within a field, by controlling the vectors (Mochida, Valencia and Basilio, 1986) and by roguing, i.e. the removal and replacement of diseased plants (Estano and Shepard, 1989). Such management tactics can be based on monitoring vector populations and disease symptoms, respectively, but evidence for the efficacy of both control methods is equivocal. Recent field studies suggest that roguing is not effective (E. R. Tiongco, unpublished) and simulation studies indicate that neither roguing or insecticide use are likely to be effective except in rather limited circumstances (Holt, 1996; Holt and Chancellor, 1996). Field-scale phylactic measures such as seed-bed protection with netting, and root-zone treatments with persistent systemic insecticides, have also been investigated. Under most conditions, infection in the seed-bed is not significant, and seed-bed protection has limited efficacy (Tiongco et al., 1993). The use of root-zone insecticide treatments at planting time may be effective in some cases (Satapathy and Anjaneyulu, 1989) but there are problems associated both with environmental toxicity and application costs.

Control of RTVD on an individual crop basis is likely to be difficult for a number of reasons. The delay in symptom expression means that a substantial proportion of plants can be infected before the presence of the disease is confirmed, so plants may act as source for a week or even longer, prior to being removed in any roguing operations. A relatively small population of vectors can give rise to high rates of plant-to-plant spread within the crop, so any attempts to kill vectors would have to be very efficient. Viruliferous vectors may also enter the crop from elsewhere and initiate infection over a long period, so any vector control would probably need to be repeated several times during the early stages of the crop.

Against this background, it is clear that a strategic approach to tungro management has more chance of success than attempts to treat individual fields when the need arises. The studies discussed in the previous section show that some assessment of the risk of serious tungro infection in a field is possible before the crop is planted. The individual farmer may respond to perceived risk by acting independently to plant a different variety or change the planting date. More importantly, if a sufficient number of farmers alter their practices, an area-wide impact may reduce the risk of tungro for the local farming community as a whole.

Discussion

In most annual cropping systems, it is possible to consider the process of infestation by a pest, or infection by a pathogen, in two stages, namely, primary infestation or infection of the crop from outside sources, and pest population growth or disease intensification within the crop. If it is possible to assess the risks at each stage then appropriate action may be taken. In this paper we have examined the decision-making associated with two rice pests, BPH and RTVD. This leads to a comparison of three different pest problems because of the differences in the ecology of BPH between temperate and tropical rice systems (Figure 10). For planthoppers in temperate rice systems, useful decisions can be made in response to information about both the risk of primary infestation and secondary spread. In tropical rice systems, the risk of secondary spread of BPH due to resurgence must be taken into account, but assessment of primary infestation is not important. For RTVD, the situation is rather different. Though disease control measures within the crop may help to prevent further primary infection elsewhere,
there is no clear evidence that disease spread within a crop can be reduced effectively. Consequently management decisions must focus on an appropriate response to the risk of primary infection.

Utilising early warnings

Strategic control of RTVD has been implemented in South Sulawesi using a government controlled programme to rotate cultivars with different degrees of resistance. This was designed to try to prevent the development of populations of leafhoppers with high ‘virulence’ to a particular variety or group of varieties. Planting dates were also manipulated in an attempt to avoid peak leafhopper numbers coinciding with the crop growth stage most vulnerable to tungro infection. This also had the effect of synchronising planting to produce more definite breaks between crop seasons (Sama et al., 1991). Such adjustments in the cropping regime may be warranted in highly tungro-prone areas. As infection pressure drops, however, farmers may revert to other practices if these are more convenient or more profitable. It is also worth noting that in many rice areas, the control measures adopted under the South Sulawesi scheme could not be implemented for practical reasons, e.g. insufficient water, labour and credit may all influence planting dates. In general, it will only be worthwhile for farmers to adopt such measures if the risk of tungro occurrence is clearly high enough to outweigh the various disadvantages.

If it is generally true that the risk of significant tungro incidence is high at only relatively short distances from sources, then any sudden outbreaks must arise because fields with relatively low incidence go unnoticed but provide sufficient inoculum to cause more significant problems nearby. Detection of such low levels of tungro infection prior to serious outbreaks in a locality would be an essential part of RTVD risk assessment. The relatively small scale on which RTVD dynamics appears to operate may allow a village to collaborate and assess the risk for the immediate locality, so allowing more timely switching to resistant varieties or modification of planting dates to reduce inoculum carry-over between crops. It may even be feasible for growers to respond to perceived risk on a field-by-field basis.

For BPH in temperate areas, the geographic scales involved in risk assessment are vastly greater because planthoppers may migrate hundreds of kilometres. A general indication of the risk of planthopper invasion over a relatively large area may be all that is reasonable, given the plethora of interacting factors which may affect migration. Individual farmers or groups of farmers can respond to forecasts by purchasing insecticide: however, in Zhejiang Province, China, a high level of local heterogeneity in the level of planthopper immigration (Cheng and Holt, 1990), means that such advance purchases may not be needed. Field monitoring must, therefore, remain a key feature of planthopper management decision-making. Other sectors of the insecticide market can make good use of forecasts in order to adjust production or supply, but a detailed spatial forecast may not be needed by decision-makers operating at province level. In the development of all pest forecasting systems, there is a need to match the precision of the forecast to the needs of the decision-makers (Day and Knight, 1995).

Finally, we note that BPH migration may also have an impact on management other than through the forecasting of outbreaks. For example, long-range migration may be important in the spread of BPH-borne rice diseases such as grassy stunt and ragged stunt, or the spread of BPH genotypes which carry resistance to insecticide or which are able to overcome the varietal resistance of rice plants. The degree of insecticide resistance found in Japan is probably dependent on insecticide use in areas of China and Indochina where the Japanese populations originate. In the past, although BHC-resistance in BPH populations increased rapidly during the season in Japan due to frequent applications of insecticide, susceptibility to BHC was restored each summer with the arrival of immigrants from less-treated areas (Nagata and Mochida, 1984). However, cases where susceptibility has been restored are now less common, probably because increased insecticide use in the immigrants’ source areas has led to stronger selection pressure for resistance in these areas (Hirai, 1993). There is also evidence that other qualitative changes (e.g. in ‘biotype’) in the BPH populations immigrating into Japan have followed similar changes in putative tropical source areas (Kisimoto and Sogawa, 1995). Regular monitoring of BPH for traits such insecticide resistance, or the ability to ‘break down’ previously-resistant rice cultivars, is necessary in order to provide warnings of potential constraints to the effective management of this pest.

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