VARIABLE RATE IRRIGATION ON CENTER PIVOTS. WHAT IS IT? SHOULD I INVEST?

R. Troy Peters[1], Behnaz Molaei, and Markus Flury[2]

ABSTRACT

Variable rate irrigation (VRI), also sometimes referred to as 'precision' or 'site-specific' irrigation, is the ability of an irrigation system to apply different amounts of water to different areas of the field. This paper discusses the various VRI options for center pivots, when they might save water, energy and create higher crop yields, and when it might be unreasonable to expect these kinds of improvements. Some of the remaining challenges associated with VRI are discussed, and a simple soil-water balance model is used to illustrate water savings estimates from various soils and how VRI might be used to take advantage of significant, in-season rainfall events.

VARIABLE SPEED IRRIGATION VS. VARIABLE ZONE IRRIGATION

Recently center pivot manufacturers and some third party equipment dealers have been offering variable rate irrigation (VRI) as an option or upgrade on their pivots in a couple ways: variable speed irrigation, and variable zone irrigation.

Variable Speed Irrigation does not require additional hardware on the pivot. It simply uses a more sophisticated control panel that will slow down or speed up the pivot to apply more or less water in different areas of the field. Many of the newer pivot control panels already have this ability built into them. After-market solutions from third-party equipment dealers usually mount on the last tower of the pivot, have an integrated GPS receiver to determine field position, and interrupt and re-send the movement control signal to the last tower to vary the speed of the pivot in different areas of the field. Despite variable speed irrigation's obvious limitations to variations only in pie-shaped wedges (Figure 1), variable speed irrigation is fairly low cost ($2,000 - $4,000) since the only modifications to the pivot are to the pivot electronic controls. These costs will likely decrease over time. The overall pivot flow rate remains constant.

1. Professor and Extension Irrigation Specialist. Irrigated Agriculture Research and Extension Center. Washington State University. 24106 N. Bunn Rd., Prosser, WA. 99350. troy_peters@wsu.edu.
2. Professor of Soil Science. Washington State University. Puyallup Research and Extension Center. 2606 W Pioneer Ave., Puyallup, WA. 98371. flury@mail.wsu.edu.

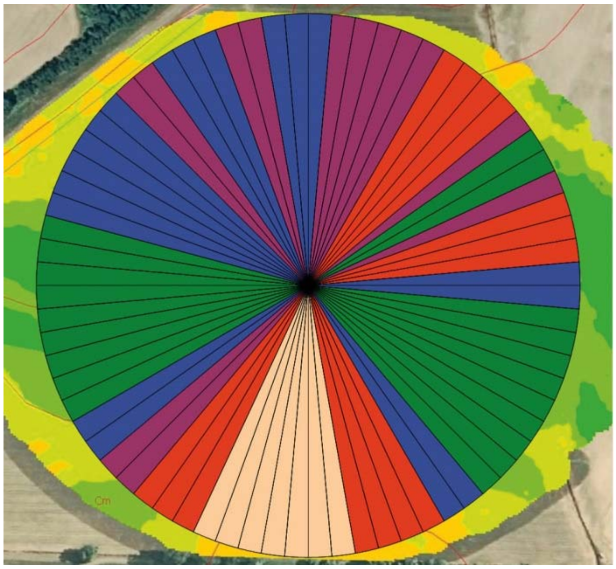

Figure 1. Variable Speed Irrigation. The pivot varies travel speed to apply variable amounts of water to defined zones within the field. Colors indicate areas with different amounts of water applied. Image used by permission from pivotirrigation.com.au.

Some additional useful applications for variable speed technology:

- On a pivot that can't go all the way around (a "wiper") it is possible to vary the speed going into or coming out of the hard stops (ends of the field where the pivot must reverse direction) to avoid running the pivot in overly wet areas in an attempt to reduce wheel-tracking issues. For example: if the wiper is applying 0.5 inches in a pass (1 inch for every back-and-forth wipe), the pivot might speed up to apply 0.2 inches of water in the 20 degrees of angle before the hard stop so the field stays drier. Then after reversing, slow down to apply 0.8 inches until it reaches the 20 degree mark again where it speeds up slightly again to return to applying 0.5 inches.
- In areas of the field where infiltration is an issue due to tight soils or steep slopes, it is possible to speed up to wipe back and forth across that area of the field to allow additional time between water applications for water to infiltrate and move deeper into the soil before water is again applied to the surface. For example: If there is always runoff on a slope between 20 and 40 degrees, and the grower is applying 0.75 inches of water in a clockwise rotation, the pivot could speed up at 20 degrees to apply 0.25 inches over the trouble spot, then reverse at 40 degrees to apply 0.25 inches, travel back to 20 degrees where the pivot would again reverse to apply 0.25 inches (for a total of 0.75 inches on the trouble spot). The pivot would then slow down at 40 degrees to apply 0.75 inches to the rest of the field. The same total amount of water was applied to the trouble spot, but the back-and-forth movement gives more time between water applications for the water to move into the soil in that spot hopefully increasing infiltration and reducing runoff.
- Speed up slightly when climbing hills to account for tire slippage (Chavez et al., 2010).

Variable Zone Irrigation includes the ability to vary the speed of the center pivot as it moves in a circle *and* vary the application rate along the pivot lateral (Figure 2). Variations in the application rate along the lateral works in conjunction with variations in the pivot speed creating the ability to apply a wide variety of irrigation depths to different areas of the field. The application rate along the lateral is usually varied by pulsing sprinklers on and off for various amounts of time. In some cases, zones of sprinklers are controlled independently, in other cases every sprinkler is controlled independently. Because additional hardware must be mounted on the pivot, as well as more sophisticated control technology, variable zone irrigation is significantly more expensive than variable speed irrigation ($15,000 - $25,000; Milton et al., 2006). These costs will also likely decrease over time. Variable zone irrigation is much better at responding to the spatial variations in the field. Turning sprinklers on and off varies the overall flow rate to the pivot and therefore a water delivery system that can absorb these variations is necessary.

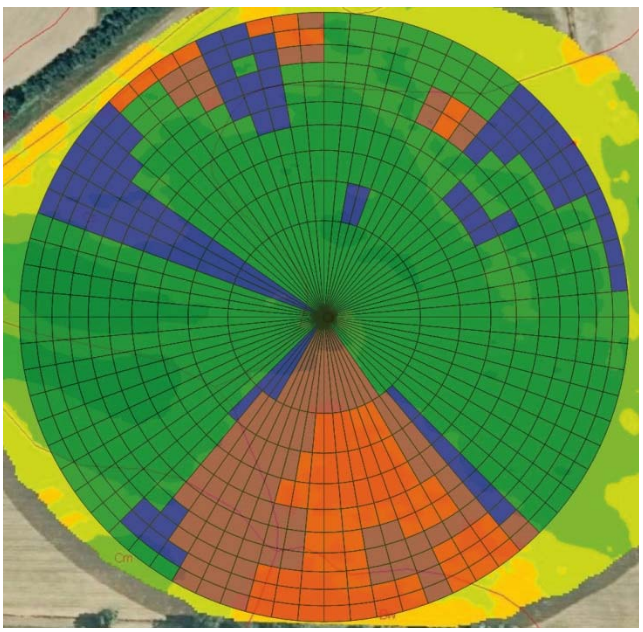

Figure 2. Variable Zone Irrigation. The pivot varies both travel speed and application rate along the lateral to apply variable amounts of water to defined zones within the field. Colors indicate areas with different amounts of water applied. Image used by permission from pivotirrigation.com.au.

WHAT OTHER RESEARCHS HAVE FOUND

Most studies have shown that center pivot VRI systems basically work as advertised. They can apply the targeted amount of water to the different areas of the field as prescribed and can do so in a relatively uniform manner. The demarcation between these “zones” is of course limited by the overlap (wetted radius) of the sprinklers. The found that the pulsing, or switching the nozzles on and off to vary the application rates did not negatively affect the uniformity within that zone (Han et al., 2009; Dukes and Perry, 2006; Sui and Fisher, 2012; Perry and Pocknee, 2003; Perry et al., 2004; Perry et al., 2007; Perry et al., 2016; Yari et al., 2017; Sui and Fisher, 2015; Moore et al., 2005; Gossel et al., 2013; Hillyer et al., 2013; Kim et al., 2006; Higgins et al., 2016; O'Shaughnessy et al., 2011; O'Shaughnessy et al., 2012; Zhao et al., 2015; Chavez et al., 2010).

Because the conditions under which VRI can be profitable do not apply to all fields, many researchers found that VRI does not always save water or conserve power (Stone et al., 2010, Haghverdi et al., 2015, Barker et al., 2018). Israeli researchers found using simulation models that adopting practices to increase infiltration and using irrigation systems with high uniformity increased total yields per unit of applied water, but that the impacts of VRI were ambiguous (Feinerman and Voet, 2000). They also found that increasing the number of management units in a field did not necessarily result in more optimal water use, and that VRI did not guarantee savings and in many cases could yield the opposite result.

Several researchers used computer simulations to show that using VRI on center pivot fields with large differences in water holding capacities in humid regions with frequent, heavy rainfalls during the growing seasons had the potential to save significant amounts of water and reduced deep percolation (Hedley et. al., 2009, and 2010; Ho, 2016; Nguyen et al., 2015). These simulated benefits depend on the base line, which might be suboptimal (see discussion of Figures 5, 6, and 7 in Appendix A). Hedley et al. (2010) also found that larger water savings were related to years with rainfall events during the irrigation period. These studies show that large differences in the water holding capacities in the field, and frequent, large rainfall events strengthen the potential savings of VRI from rainfall capture. A simulation done for the entire state of Nebraska estimated that the statewide potential water savings from FRI (everybody doing it) to be 1.3%, with 13% of fields being able to save 1 inch or more per season, and 2% of the fields able to conserve 2 inches of water or more per season.

There were only a few studies that actually collected field data on the water savings of VRI. One of study did not find significant water savings from VRI (Stone et al., 2011). However, Sui and Haijun (2017) used VRI to use 25% less water in Mississippi and found slightly increased yields. McDowell (2017) found that VRI in New Zealand reduced leaching (different from water savings) by 85%. These results are also from high rainfall areas.

Adoption of VRI has been generally limited and its use by early adopters has not always been sustained (Evans et al., 2012). The complexity of installing, maintaining, and effectively managing VRI systems has been a significant barrier to adoption. In many instances the economic returns from adopting these technologies have not been easy to consistently demonstrate (Feinerman and Voet, 2000; Berne et al., 2015). However, increased costs of water and energy, and severe water limitations will likely increase the financial incentives to adopt VRI (Evans et al., 2012).

IS IT WORTH IT?

Is variable rate irrigation right for your pivot? The answer is, "it depends". The upfront costs of VRI, especially variable zone systems, can be substantial. The ongoing management costs can also be high. In many cases, modifying the management of existing soils can eliminate the perceived need for VRI. On the other hand, in certain instances it may save substantial amounts of water in the long run. A discussion of when water savings should, and should not be expected follows.

Variable rate irrigation in response to variable soils

The water use of healthy crops with access to sufficient water and nutrients will not be significantly dependent on what kind of soil they are grown in. Crops grown in sandy soils will not use significantly more or less water than crops grown in silt or clay soils. So, for example, even in a field with highly variable soils, all areas of the field will be using ¼ inch of water every day. Because of this, applying different amounts of water to different areas of the field only makes sense if the crops are getting water from another source besides where the center pivot irrigation system is applying it, or if the crops are using less water in some areas of the field due to disease or pest pressure. More discussion on this follows below.

"I apply more water to the sandier areas of my field during each irrigation."

Sandy soils do not need more water. They cannot hold the extra water. If they are watered more each time then the additional water will be lost to deep percolation. They need to be watered in smaller amounts more frequently. Because of this, if the entire field is managed as a whole to prevent water stress and water losses to deep percolation in the *sandy* areas of the field then *all other areas* of the field will be fine (Figures 3 and 4).

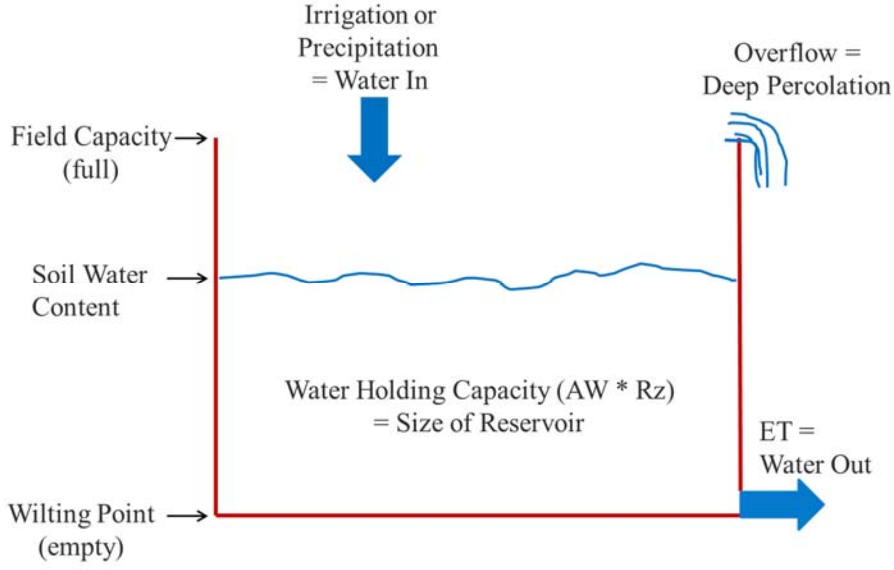

Figure 3. Soil serves as a reservoir for water and nutrients. The size of the reservoir depends on the soil's water holding capacity (how much water it can hold per inch of root depth; AW), and the rooting depth of the soil or crop (Rz). Irrigation or precipitation that infiltrates into the soil when there is space in the soil to hold that water is stored for later use by the crop. If more water is applied to the soil than the soil can hold, then that extra water is lost (leached) out the bottom of the root zone (shown as overflow). Crop water use, or evapotranspiration (ET), is largely independent of the soil type.

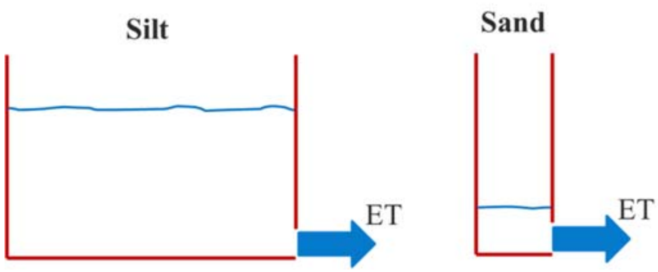

Figure 4. If the same field has areas that are both silt and sand, then if they both started full, then after a given amount of time the sandy areas will be getting dry and exhibiting crop water stress, while the silty areas will appear fine. If the entire field is managed for no stress, or no water losses to deep percolation in the sand (overflow in the diagram), then the silty areas will also be fine. If more water is applied to the sand when refilling the soil, that additional water will be lost to deep percolation.

Some simulations were done using Irrigation Scheduler Mobile (http://weather.wsu.edu.ism, Peters, 2014) to model what the soil water content would look like in a sandy area of the field (Figure 5) and in a silty area of the field (Figure 6) if the whole field was managed for the sand. A similar simulation was done of the sandy (Figure 7) and silty (Figure 8) areas of the field if instead the whole field was managed for the silt. It can be seen that when the entire field is managed for the soils with the lowest water holding capacities that all areas of the field are fine. This is, however, not the case if the field were managed for the soil with the larger water holding capacity (the silt). In that case, the sand would show water stress.

"I have runoff on the steeper slopes, and the crop is water stressed in that area of the field so I apply more water to those slopes."

If water is already running off a slope, applying more water will result in *all* of the additional water also running off, possibly causing erosion, and that additional runoff water may pond in the low spots of the field, making the overall irrigation and crop uniformity problems in the field worse. If the water is running off, then less water, not more, needs to be applied to slopes in a pass to ensure that the applied water infiltrates into the soil. But to ensure that these areas of the field don't fall behind the rest of the field this means speeding the pivot up on the entire field as spatial variation would result in these areas falling permanently behind. The "wiping" method described above can help to reduce or eliminate runoff. As an alternative to speeding the pivot up, or as additional runoff-prevention measure, runoff in these steep sloped areas can be mitigated by changing the tillage methods, and possibly the crop row orientation. Modifying the sprinkler system so that it applies water at a slower *rate* can also help improve infiltration. This might include using boombacks or draping every other sprinkler around the outside of the truss rods, or using sprinklers with a much larger wetted radius. If the soil is hydrophobic (water balls up and runs off of dry soil instead of infiltrating) then using soil surfactants may also help with infiltration.

Because of these things, *in low rainfall areas purchasing VRI in response to highly variable soils has little opportunity to increase profitability in comparison to optimally managing the entire field uniformly for the problem soils.*

SITUATIONS WHERE VRI CAN CONSERVE WATER AND IMPROVE PROFITIABILITY

Do not irrigate non-cropped areas

VRI can save water, agrochemicals, and reduce maintenance problems by completely shutting the water off in areas of the field that should not be irrigated (Sadler et al., 2005). These might include rock piles, ponds, or streams, waterways or roads that cross through the field or areas under the irrigation system that are otherwise not farmable. Sometimes pivots overlap. Shutting the water off on one of these pivots in the overlapped areas will reduce overwatering those areas. These constant, unchanging prescriptions where the water is turned off completely will result in the largest water and power savings at the lowest long-term management costs. Consequently most VRI systems being sold are primarily being used in this application (Evans et al., 2012). Avoiding off-target application of agrichemicals or liquid wastes is another large driver for the adoption of VRI.

Areas of the field getting water from other sources

VRI can conserve water by applying less water to areas of the field where the crops are getting water from sources. This may be either a high water table, or an area where water is ponding in the field due to runoff from sub-optimal operation of the pivot, or from water running onto the field from outside sources. Watering these areas less can reduce over-irrigation, saturation of soils, losses of nitrates through leaching, and losses of yield due to waterlogging (Sadler et al., 2005). It may be necessary to modify the VRI prescription (variable irrigation map or plan) throughout the season to irrigate these areas more or less because the alternative sources of water may not be constant or able to keep up with ET throughout the entire season.

Leave room in the soil to capture rainfall

In humid areas where there is significant in-season rainfall, periodically shutting the water off to the areas of the field with larger water-holding capacities will leave space in the soil to capture and hold anticipated rainfall. The sandy areas will still have to be irrigated on a regular basis to avoid stress because of their small water holding capacity; however, the water in the silty or clay areas can be depleted. Then, during significant rainfall events, there will be capacity to hold this rainfall in the silt or clay areas of the field. At these events there will be unavoidable rain water losses to deep percolation in the sandy areas. Doing this accurately requires additional data collection of the soil water content in the different areas of the field, good irrigation scheduling techniques, and in-season modifications to the VRI prescription in response to timing and depth of the precipitation events. See the section in Appendix B on 'Soil Water Simulations of Various Scenarios' and Figures 9, 10, and 11 for a better explanation.

Different crops in the same field

VRI will allow growing different crops in different areas of the field and managing the water for these areas separately. This may be especially useful to those who cannot or do not want to plant in pie-shaped sections. It also may be especially useful for researchers or seed growers who have a wide variety of different plots, crops, or water treatments under the same pivot.

Avoid overwatering the inside span

The sprinkler flow rates required on the first span of a center pivot (nearest the pivot point) are so low that these small nozzle sizes can be plugged with small debris in the water. Because of this, many pivot dealers put on larger nozzles. Variable zone irrigation could be used to periodically shut these nozzles off to avoid over-watering these two inside spans. Allowing the canopy in these areas to dry more often may reduce plant diseases and therefore disease spreading to other areas of the field.

Variations in Crop Water Use (ET)

If there is a large variation in crop water use across the field (ET) applying *less* water to the areas where the ET is *lower* might conserve this water. These lower ET rates may be due to disease or pest pressure among other possibilities. Because these areas are using less water, applying the same amount of water as other areas may result in additional water losses to deep percolation. This might be counterintuitive because most people want to water areas that are not doing well more, not less.

Use pivot as a variable rate sprayer

VRI may come in very handy when you use it for chemigation or fertigation and you wish to apply these at a variable rate. This can be especially beneficial for those applying liquid wastes.

Control for uniform dry down

In some instances it may be desirable for the crops in all areas of a field with highly spatially variable soils to experience water stress at the same time. In this case it may be desirable to restrict irrigation water to areas that have greater water holding capacity (deep silts or clays) sooner so that the soil profile will be depleted at about the same time as the areas with lower water holding capacities (shallow or sandy soils).

Variable rate irrigation will be more profitable if the costs of water, or the marginal opportunity cost of lost water is high. The marginal opportunity cost of lost water is greatest when growing high value crops and water is already very limited.

CREATING AND MODIFYING VRI PRESCRIPTIONS. NOT TRIVIAL!

The off-the-shelf VRI systems sold by pivot manufacturers and third party dealers have been shown to be effective at applying the targeted amounts of water to the desired locations in the field (Dukes and Perry, 2006; O'Shaugnessy, et al., 2013; Higgens et al., 2015a). In other words, the control systems and hardware work well and the equipment's ability to apply variable rates across the field is not a barrier to the adoption of VRI. The primary barrier is developing and modifying VRI prescriptions in a way that improves the overall profitability.

Prescriptions are the maps, or plans for how the irrigation amounts will be varied in the different areas of the field. These are often developed based on experience, GPS or GIS mapping, and/or GPS-referenced soil sampling. Electrical conductivity (EC) mapping, which is often used to indicate the differences in soil texture or water holding capacity throughout the field, is also widely used. This data collection is often time consuming, expensive, and plagued by high degrees of uncertainty (Higgens et al., 2015b) and sources of variability. In addition it must be done by fairly educated and skilled (i.e. expensive to employ) personnel who are often hired consultants. Once the data that characterizes the variations in the field has been collected, it is not always clear how to vary irrigation amounts and timing in response to this data. Additional research is ongoing on these topics.

Further, irrigation decisions must be reevaluated many times over a season. Crop performance relative to other areas of the field, the soil surface conditions that affect infiltration rates and the various alternative sources of water (size of the pond in your field) rarely remain constant throughout a growing season. In addition, using variable rate irrigation to leave space in soils with larger water holding capacities to take advantage of water from anticipated rainfall events requires in-season modifications to avoid stressing the lower water holding capacity areas and to adjust for the fact that the anticipated rainfall may not materialize. Therefore, it may be necessary to modify the prescriptions many times throughout the season. Such modifications can be especially challenging with continuously variable soils. This greatly increases the amount of data collection, analysis, decision-making, and modifications made to the VRI prescriptions throughout the season. This can be time consuming, complex, and therefore expensive.

However, if the specific on-farm conditions allow the use of a consistent VRI over time then significant savings in management time and costs can be achieved and will likely result in considerable water savings. For instance, when there are non-cropped areas which can be left non-irrigated, or if the crops are getting water from a consistently high water table then the VRI prescription need not change over time, and therefore these scenarios have the greatest potential for long-term implementation and measurable water savings.

CONCLUSION

Variable rate irrigation gives a grower the ability to vary the amount of water that is applied to different areas of the field. On center pivots, this can be done fairly simply and relatively inexpensively using variable speed irrigation. However, the spatial variations are limited to pie-shaped wedges. There are several other applications of variable speed irrigation besides VRI that can provide benefits in certain fields. Variable zone irrigation includes the ability of the system to vary both the speed and the amount of water applied along the lateral. It is more sophisticated, and flexible, but also much more expensive.

In-field variations in soil water holding capacities and infiltration rates can be largely mitigated by proper water management to the entire field as a whole for the problem soils. If the whole field is irrigated to avoid deep percolation and water stress in the soils with the lowest water holding capacity, the rest of the field will be fine. Likewise managing the field as a whole to limit runoff in certain problem areas has little negative effects on the rest of the field.

Variable rate irrigation may provide water and power savings, or crop yield benefits in the following circumstances: withholding irrigation in non-cropped areas, not irrigating areas of the field that are getting water from other sources, keeping the soil water content at a level so that rainfall can be captured (rainfall harvesting), varying irrigation of for the different water needs of different crops in the same field, responding to spatial variations in crop water use (ET) due to crop health variations, to use pivot as a variable rate sprayer or waste disposal system, or to avoid overwatering the inside span of the pivot.

The VRI systems currently being sold can fairly accurately implement uploaded VRI prescriptions. However, the data collection, analysis, and creation of optimal VRI prescriptions for a specific field's needs can be complex, time consuming and expensive, especially since many field situations require these prescriptions to vary both in time, and in space. This is currently a significant barrier to the profitable use of VRI.

Variable speed irrigation currently has greater potential to be a good investment. Variable zone irrigation systems that are used to consistently avoid irrigating non-cropped areas are likely to be the most manageable and beneficial, especially when injecting agrichemicals or waste products and it is unlawful to apply these to non-cropped areas.

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