MAPPING TURF EVAPOTRANSPIRATION WITH HIGH-RESOLUTION MULTISPECTRAL AERIAL IMAGERY

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Abstract. Multispectral imagery with visible, near-infrared, and thermal wavebands was used to spatially estimate evapotranspiration (ET) in Berthoud, CO. The METRIC (Mapping Evapotranspiration at high Resolutions with Internal Calibration) energy balance model was used to estimate turf evapotranspiration from aerial multispectral imagery collected in 2011. The METRIC model was developed using Landsat satellite imagery but is adaptable to other satellite imagery with similar wavebands available. The METRIC model was also recently adapted for aerial imagery with limited reflective bands and a thermal band.

Following adaptation for aerial imagery, the METRIC daily ET for turf at Berthoud, CO was compared to daily ET from 44 mini-turf weighing lysimeters on 31 August 2011. Combinations of ETo (short crop or grass reference ET) vs. ETr (alfalfa or tall crop reference ET) and alfalfa vs. turf cold pixel resulted in mean percent error of 6.20 and 6.48%, for ETo and turf cold pixel and ETo and alfalfa cold pixel, respectively. METRIC agreement with lysimeter data using ETr as the reference ET ranged from 37.5% to 48.5% mean percent error for turf and alfalfa cold pixels, respectively. On 19 July 2011, mean percent error of METRIC ET and lysimeter ET using ETo and a turf cold pixel was 6.15%. METRIC applications for turf require ETo as the reference ET in the model.

Keywords.

INTRODUCTION

METRIC (Mapping Evapotranspiration at High Resolution using Internal Calibration) is a remote sensing model to estimate evapotranspiration (Allen et al. 2007b, c). METRIC has its roots in the SEBAL (Surface Energy Balance Algorithm for Land) model (Bastiaanssen et al. 1998a, b)

METRIC was developed as a method to estimate ET in irrigated agricultural regions from Landsat imagery. One strength was that it eliminated the need for a crop classification as it was based on well-established physical and biological parameters derived from the image bands and on-the-ground meteorological data. Recommendations for use included choosing a “cold” pixel that was part of a tall crop population. “Cold” pixels then assumed the value of 1.05x the tall crop, or alfalfa, reference ET value (ETr). For agricultural applications, ET is usually referenced to "tall" crop reference evapotranspiration (ASCE-EWRI, 2005), which is considered comparable to alfalfa reference evapotranspiration.

As METRIC applications have expanded, some potential limitations of the method have been encountered. Using multispectral aerial imagery, Chavez et al. (2012) found that using ETo (grass or short crop based ET) instead of ETr in a METRIC estimation in an advective environment improved agricultural crop ET agreement with lysimeter values. Also, in that study, alfalfa or other tall crop pixels were not cooler than grass (short crop) pixels in the limited aerial imagery frame and were not selected as the cold pixels.

On three dates in 2011, multispectral aerial imagery was acquired over Northern Water's Conservation Gardens in Berthoud, CO. The purpose of this paper is to compare turf mini-lysimeter ET to METRIC ET with various combinations of ETr, ETo, and alfalfa vs. turf cold pixel. Results of the comparison will be used in future analysis of turf ET at the Conservation Gardens site. Because full cover alfalfa or other tall crop fields were not consistently available in the extent of the aerial image, it was imperative to verify that turf, the main subject of the aerial campaign, could be used as a reference for the cold pixel, and to verify whether ETr or ETo was the appropriate reference ET value to use in METRIC. Turf ET is typically referenced to ETo, so it is consistent to attempt to use that value in a METRIC turf analysis.

MATERIAL AND METHODS

Imagery

Multispectral aerial imagery was acquired on 19 July, 12 August, and 31 August 2011 via the Utah State University airborne multispectral remote sensing system (Chavez and Taghvaeian, 2012). Table 1 shows time of acquisition (Chavez and Taghvaeian, 2012). Flight and camera details are also found in Chavez and Taghvaeian, 2012. Reflective band resolution was 0.2 m and thermal band resolution was 0.6 m.

Table 1. Image acquisition times (24-hr basis, Mountain Standard Time).

Date	Morning flight	Afternoon flight
19 July 2011	1131	1327
12 August 2011	1055	1242
31 August 2011	1045	1347

The aerial imagery was georegistered and radiometrically corrected. Reflectance panels were used to calibrate the reflectance bands. Minor adjustment of pixel alignment among image dates and thermal and reflectance bands standardized the images for subsequent GIS analysis.

Only the 31 August 2011 morning image was used in this analysis, as full cover alfalfa was present in the image only on that date. The afternoon flight on this date had significant cloud cover. Lysimeter and METRIC analysis from 19 July 2011 were used to independently check the model and parameters generated from 31 August 2011. The lysimeters were hand-watered during the day on 12 August 2011, so lysimeter data were not available for that date.

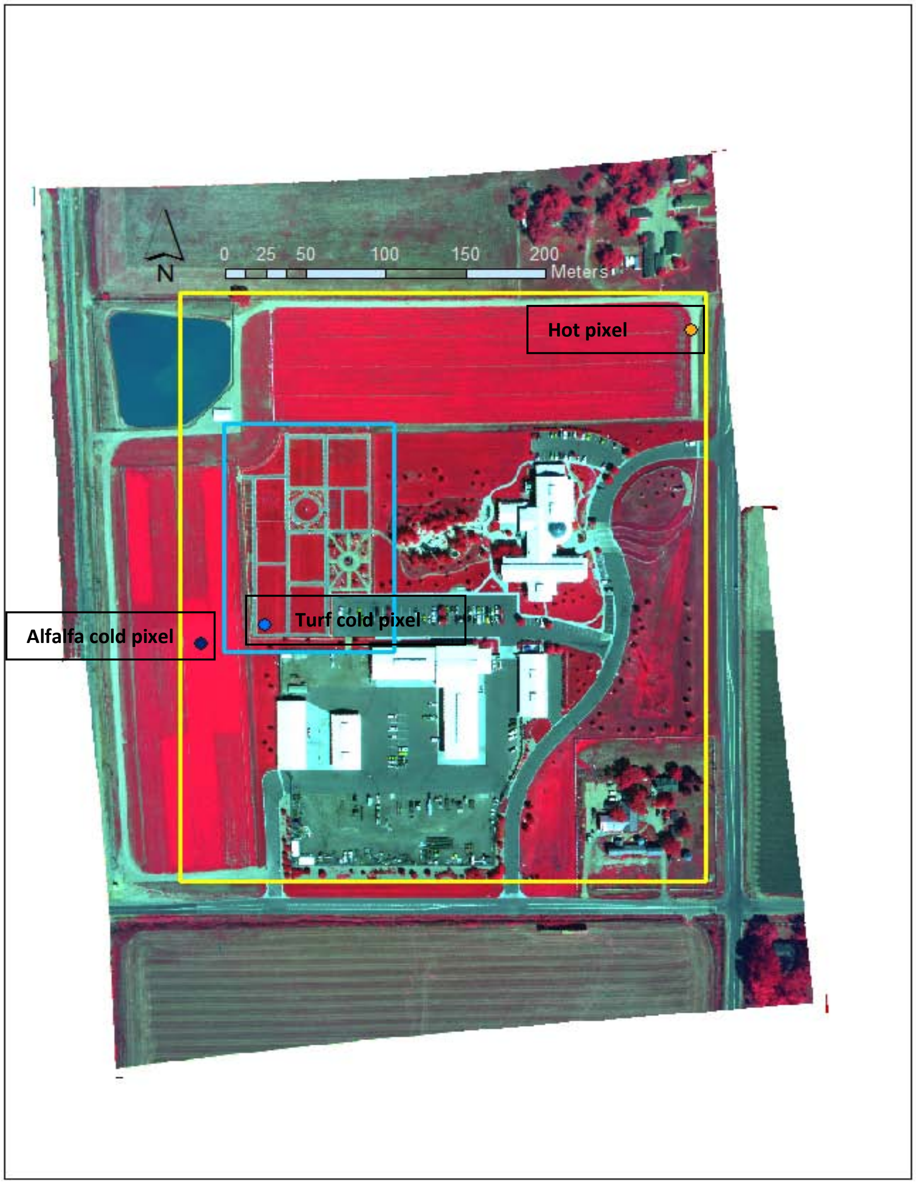

Figure 1. Aerial false color image on 31 August 2011 of Northern Water's property near the Conservation Gardens are outlined in blue. The clipped image is outlined in yellow. The alfalfa field in the analysis is located to the west of the Conservation Gardens. The cold and hot pixels are labeled in the figure.

METRIC

Details of the METRIC model are found in numerous references (Allen et al., 2007a, b, c). Conceptually, METRIC calculates ET via energy balance algorithms based on short wave reflective and thermal waveband imagery, such as Landsat satellite images. The energy used for evapotranspiration is calculated as a residual of net radiation minus soil heat flux and sensible heat flux. Because the remotely sensed data are indicative of current crop status and the algorithms are based on well-established physical processes, METRIC provides a direct method of calculating ET.

While METRIC was originally developed with Landsat satellite imagery, recent applications of the model used aerial imagery and were adapted for the more limited wavebands of the aerial data (Chavez et al., 2012). In the Northern Water application, modifications were also made to accommodate the limited spectral bands of the aerial imagery.

In this application, METRIC surface albedo calculation was modified for the limited band aerial imagery following concepts and procedures in Tasumi et al. (2008), the METRIC manual (Allen et al. 2007a), and in (Brest and Goward, 2007). Atmospheric correction was based on SMARTS2 (Gueymard, 1994, 1995) output for each date and image acquisition time, following concepts in Tasumi et al. (2008) and Allen et al. (2007a).

Also in this analysis, the SAVI (Soil-Adjusted Vegetation Index, Huete, 1988) L factor (the soil-brightness adjustment factor) was set at 0.05 after testing with various values of L. As L approaches 0, the SAVI becomes equivalent to NDVI, the Normalized Difference Vegetation Index (Rouse et al., 1973). Allen et al. (2007a) recommended L = 0.1 for Idaho conditions.

The cold pixel was selected from coldest turf pixels in the Conservation Gardens and coldest alfalfa pixels in the west alfalfa field. The hot pixel was selected from the limited range of bare soil pixels in the image, primarily from the east or north edges of the north alfalfa field, where there is a narrow soil roadway and a narrow transition from field to roadway. A simple daily soil water balance was used to estimate ET of the bare soil so that $H = RN - G - ET_{bare\ soil}$.

To maintain consistency with the chosen reference ET methods, EToF and ETrF were used to extrapolate the instantaneous METRIC ET values to daily ET values. EToF and ETrF are the instantaneous fractions of calculated actual ET to reference ET. EToF and ETrF are assumed to be relatively stable throughout the day.

Weather data

Weather data necessary for input into the METRIC model were obtained from Northern Water’s Berthoud weather station, sited in the center of the Conservation Gardens. The weather station is maintained regularly and instrumentation checked or calibrated at least annually. More information about Northern Water’s weather network, reference ET calculations, equipment,

operating standards, and sites can be found here:
http://www.northernwater.org/WaterConservation/BackgroundInfo.aspx.
Northern Water uses the ASCE-EWRI Standardized Reference methods (ASCE-EWRI, 2005).

Lysimeters

The 44 small turf weighing lysimeters were installed in 2009 and turf established in 2010, with 2011 the first full year of operation. Four replications with 11 turf mixes or blends were irrigated as for high quality turf. Briefly, lysimeters were 0.61 m deep, and 0.3 m in diameter, filled with a sandy loam soil. Each lysimeter was centered in a 1.22 m x 1.22 m plot of the same turf. The plot was large enough to have thermal pixels fully within the plot bounds. Areas within each lysimeter plot were digitized on pixel bounds for pixel data extraction in each plot area.

Weighing load cells were electronically logged at 15 min intervals. Details of construction and the first two years of the lysimeter study can be found in Crookston and Hattendorf (2012).

Irrigation was scheduled by soil water balance from the adjacent Berthoud weather station. A base irrigation was applied, and individual lysimeter plots were then hand-watered up to each individual lysimeter irrigation specification for that date.

Irrigation

The west alfalfa field was irrigated on several dates in 2011 (Figure 2). The cold pixels were located in a plot that was part of an alfalfa irrigation study. This plot was watered once after 1st cutting, with no irrigation after 2nd cutting. Irrigation resumed after 3rd cutting. This plot had temperatures consistent with temperatures in full irrigation plots, which could not be included in the clipped image.

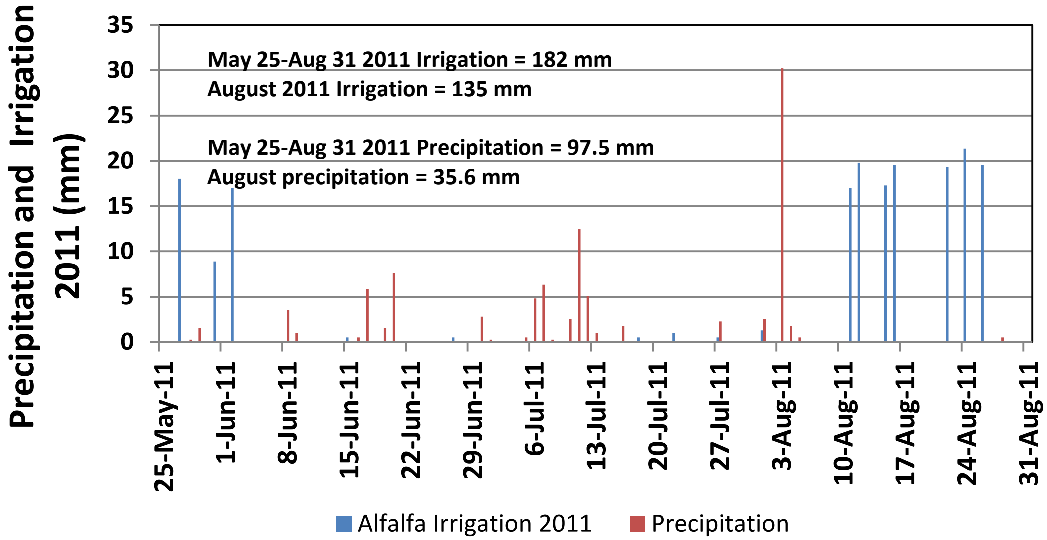

Figure 2. Precipitation and irrigation in the alfalfa plot where the alfalfa cold pixel was selected. The lysimeters were irrigated 6 days prior to the 31 August flight.

GIS was used to extract individual lysimeter METRIC ET values for comparison to the weighing lysimeter data. Only data from 31 August, 2011 were used for these comparisons, as that was the only date from the three flights that had full cover alfalfa. All rainfall, sprinkler irrigation, and hand irrigation in the lysimeters from 1 April 2011 to 26 Oct 2011 are shown in Figure 3.

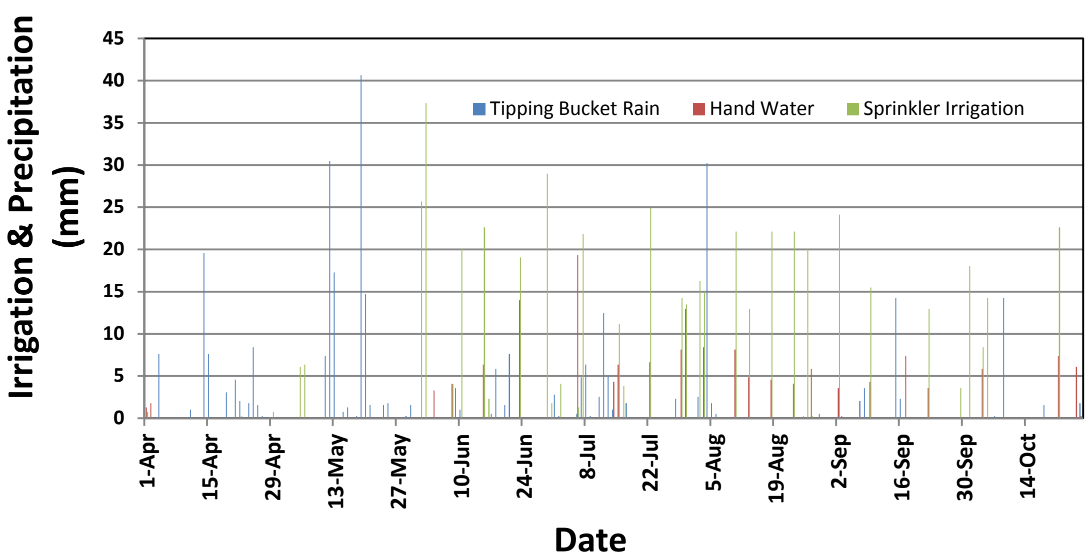

Figure 3. Lysimeter rainfall, sprinkler irrigations, and hand irrigations in 2011. Hand irrigations usually followed the base irrigation.

RESULTS

METRIC Analysis

The METRIC analysis was executed with the following cold pixel parameters (Table 2) with ETr and subsequently ETo as the reference ET used in METRIC. Each value was extracted with GIS analysis at the cold pixel point. The parameters are NDVI; LAI, leaf area index; Ts, surface temperature (deg K), and albedo. NDVI is calculated as (near-infrared [Band 4] – red [Band 3])/([near-infrared [Band 4] + red [Band 3]), with band numbers referenced to Landsat bands. NDVI is an indicator of green biomass—the higher the value, the greater the green biomass. Leaf area index is a dimensionless number commonly defined as area of leaves per unit area of ground surface. Surface temperature Ts (deg K) is obtained from the thermal band of the imagery product. Albedo is the unit less integrated surface reflectance across the full shortwave spectrum.

Table 2. Alfalfa and grass cold pixel parameters.

Cold pixel	**NDVI**	**LAI**	**Ts (deg K)**	**Albedo**
Turf	0.839	3.8	302.81	0.190
Alfalfa	0.896	5.7	299.22	0.282

Results of the METRIC analyses showed that using ETr with an alfalfa cold pixel overestimated ET values with a mean percent error of 48.54. Root Mean Square Error (RMSE) was 2.89. Error associated with all combinations of reference ET, date, and vegetation of cold pixel is listed in Table 3.

Table 3. Error associated with METRIC agreement with lysimeter data.

Date	Reference ET	Cold Pixel Vegetation	Mean % Error*	RMSE*
31August 2011	ETo	alfalfa	6.48	0.48
31 August 2011	ETo	turf	6.20	0.47
31 August 2011	ETr	alfalfa	48.54	2.89
31 August 2011	ETr	turf	37.46	2.24
19 July 2011	ETo	turf	6.15	0.42

*Mean % error = $[\sum(\text{abs}(y_{MET}\text{-}y_{LYS}))*100]/n$ RMSE= $\sqrt{[\sum(y_{MET}\text{-}y_{LYS})^2/n]}$
($_{MET}$ = METRIC; $_{LYS}$ = Lysimeter)

Although the alfalfa cold pixel was 3.59 deg C cooler than the turf pixel, this was less important to the accuracy of the METRIC analysis than the choice of grass or alfalfa reference ET. METRIC and its parent model, SEBAL, both use a scaled dT function and thus escape the limitation of using explicit surface temperature as a driver for ET (Allen et al. 2007b, Bastiaanssen, 1998a).

The upper and lower limits of evapotranspiration are effectively set by the reference ET and the multiplier chosen, in this case ETr x 1.05 or ETo x 1.05.

The reference ET places a limit on the range of ET values that can be generated from an analysis, regardless of the cold pixel temperature. Choice of ETo over ETr effectively muted the maximum ET that could occur with the given parameters even for a substantially cooler pixel.

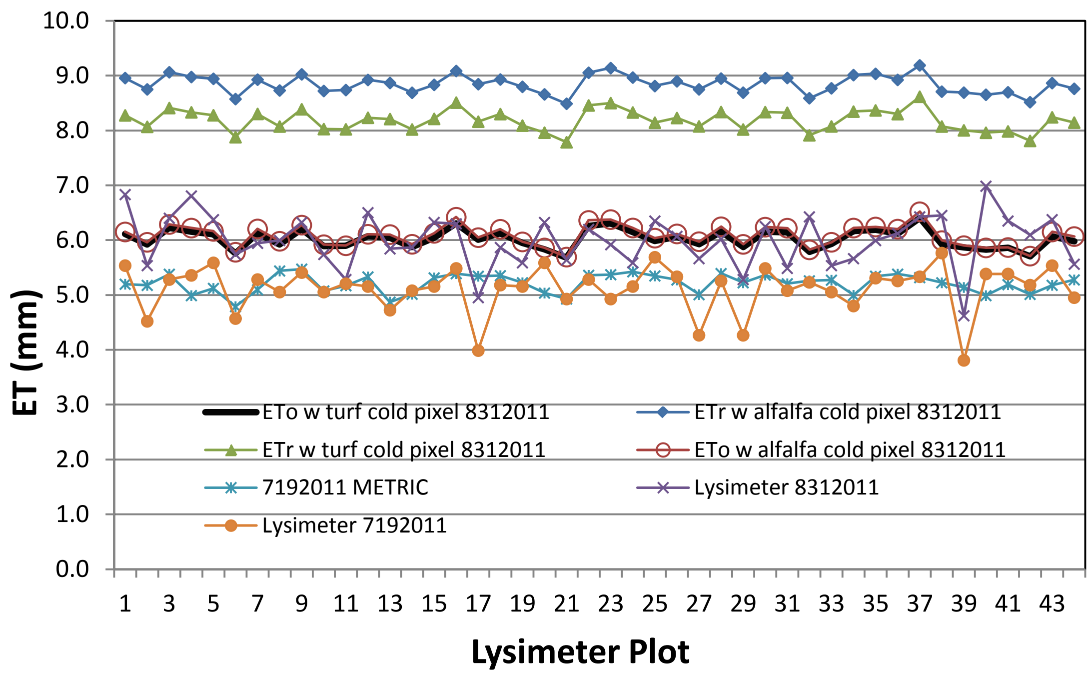

Figure 4. Extracted METRIC data points and the lysimeter data for 2 dates in 2011.

ETr with an alfalfa cold pixel systematically overestimated the 31 August 2011 lysimeter values (Figure 4). Choosing a turf cold pixel improved the estimate slightly, but METRIC still overestimated lysimeter ET. Standardized reference ET (ASCE-EWRI, 2005) is calculated at Northern Water; the separate calculations for “tall” crop and “short” crop were intended for the agriculture and landscape communities, respectively. It is clear from the results that a landscape turf application requires use of “short” crop reference ET.

Lysimeter ET for plots 17, 27, and 39 were lower than most of the other plots on both dates. These lower values were not well-tracked by METRIC. The turf in these plots (Ephraim Crested Wheatgrass) did not establish well. A factor that may have contributed to this non-agreement could be choice of SAVI L value. For this analysis, L = 0.05 yielded parameters within bounds of possible and appropriate values. This L value was more consistent with the recommended L value of 0.1 for Idaho conditions (Allen et al., 2007a) than with the original recommended L value of 0.5 (Huete, 1988).

Testing L = 0.5 led to daily ET values distant from the lysimeter values and implausible intermediate values of LAI and albedo in particular. However, further sensitivity analysis with the SAVI L value could establish a range of conditions, inputs, and plausible values. Other means of deriving the L factor, such as via MSAVI (Qi et al, 1994) might provide a more robust methodology, though this requires development of a soil line from the red and near-infrared bands. However, for specific sites, this might not be overly burdensome, if the procedure works.

There may be other factors that weigh into lack of agreement of the METRIC-calculated Ephraim Crested Wheatgrass ET with lysimeter ET, but because L was extensively tested over a range of values for this analysis, further refinement in selecting this factor may be necessary.

CONCLUSIONS

Expanding applications of METRIC create challenges in choice of reference ET and cold pixel selection. METRIC must be run with ETo as the upper limit for turf applications, at least for the ASCE-EWRI ETo formulation. Using ETr as the upper limit generated METRIC ET much higher than lysimeter ET. It is therefore consistent to search for a well-watered turf cold pixel, but in this analysis, it worked nearly equally well to choose a cooler alfalfa pixel. ET even from a colder pixel than in well-watered turf is constrained by the ETo*1.05 ceiling.

When using ETr, separation of the alfalfa and turf cold pixel ET estimates are spread apart because ETr embraces the full range of ET available to the agricultural or turf world.

This is apparently a limitation of METRIC: while a crop classification may not be genuinely necessary in most contexts, regional ET where there are large acreages of turf or sod farms may be significantly overestimated. By extension, ET of “short” crops with leaf area index or aerodynamics similar to turf may also be overestimated.

Potential limitations of this application may include methods of selecting the SAVI L value. In this analysis, the METRIC ET output could be verified against the lysimeter ET after testing a range of L values. However, most applications will not have this level of validation available. Experimentation with various suggested SAVI L values, such as L = 0.5, yielded ET and other parameters out of bounds of established typical values. It may be worthwhile to explore different methods of acquiring an L value, such as MSAVI.

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