Potential of Radar-Estimated Rainfall for Plant Disease Risk Forecast

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Lack of site-specific weather information has been a major limitation in application of decision support systems in plant disease management because existing weather stations are too sparse to account for local variability. Magarey et al. (17) stressed the need for site-specific weather information and extensively discussed problems associated with deployment of on-site weather stations for high-resolution weather information. To circumvent the shortcomings, they described a system known as model output enhancement technique, originally introduced by Kelly et al. (11), where interpolated upper air forecasts from a mesoscale numerical model are extrapolated to ground surface at 1 km^2 resolution using geophysical data.

Rainfall is one of the most spatially variable weather factors (1,8,14). Sufficient information on relationships between rain gauge density and rainfall spatial variability is lacking, but available data suggest that a rain gauge spacing of less than 5 km would be required to explain greater than 90% of the variability (1,8). For a rain gauge network, such a high degree of spatial resolution would be very costly and impractical. Currently, distances between existing weather stations often exceed 50 km, even for so-called densely populated regional networks, and are greater than 100 km for first-order National Weather Service (NWS) Stations (15). Rain gauges provide point source measurements. Hence, without a dense rain gauge network, spatial interpolations for locations without weather stations often produce inaccurate precipitation measurements.

A wide variety of fungal and bacterial plant pathogens are dispersed by rain splash and/or wind-driven aerosols. In addition, rain provides high humidity (or free water) for propagule germination and infection and, consequently, many plant disease epidemics are associated with periods of rainfall (3). In semi-arid climates, like the Texas Panhandle, rain is the principal source of high humidity required for activity of many plant pathogens. It has been shown to be a major driving force behind sorghum ergot epidemics, caused by *Claviceps africana*, in the Texas Panhandle (25). During the last few years, we have been experimenting with the application of radar rainfall estimates for site-specific ergot risk assessment as an alternative to gauge-based measurement (26).

Radar-based precipitation estimates have greater spatial coverage and resolution than gauge-based point precipitation estimates (19). Therefore, radar-estimated rainfall is more applicable than gauge-based rainfall estimates for interpolation and regional risk assessment. There have been reports of the successful use of radar precipitation estimates for site-specific plant disease management (7,12). However, questions often arise about the accuracy of radar-estimated rainfall and its relationship to traditional gauge-based rainfall measurements. In this letter, we discuss some of the factors associated with both radar and gauge rainfall measurements, the relationship between the two methods, and the potential of radar rainfall for site-specific disease risk assessment.

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NEXRAD (Next Generation Weather Radar), also known as WSR-88D (Weather Surveillance Radar 1988–Doppler) or simply Doppler radar, so named after C. J. Doppler, the discoverer of the Doppler shift, has been operational in the United States since the early 1990s. One of the basic concepts of Doppler radar technology is the ability to detect a phase shift in pulse energy of a reflected signal (Doppler shift) after coming in contact with an object in motion (such as rain drops). The weather surveillance radar is supported and operated by three governmental agencies including the NWS (5). Deployment of NEXRAD is considered to be a major step in revolutionizing the weather forecast system in the United States (5,13). This radar system has shown marked improvements in sensitivity and delivery of meteorological and hydrological products over the earlier non-Doppler weather radars (4,21). NEXRAD generates a large number of diverse meteorological and hydrological products, including rainfall and wind velocity (13). Perhaps the most appealing product of NEXRAD to plant pathologists is the radar's spatial resolution of real-time hourly rainfall estimates. The precipitation rates are computed on a 1 km × 1° grid and averaged on a polar grid of 1° azimuthal and 2 km radial increments out to a range of 230 km (5,18). Figure 1 is a NEXRAD image of a rainstorm that passed through the northern Texas Panhandle on 11 August 1997. The smallest pixel has a resolution of 2 km radial length and the shades of gray depict levels of rainfall accumulation during the 24-h period.

The processing of radar data is a multistage procedure. The raw radar reflectivity is converted into rainfall rate (stage I) using the *Z-R* relationship (described below). The next stage (stage II) is computing of hourly mean-field rain gauge-radar corrections followed by regionally mosaicking of the hourly rainfall product (stage III) from multiple overlapping radars (5). Recently, a new procedure (known as multisensor precipitation estimator) has been introduced to improve rainfall quantification. In this latest addition, rain gauge, radar, and satellite data are merged (on a pixel-by-pixel basis) to generate optimal multisensor rainfall grids. The final hourly regional precipitation product is remapped onto a polar stereographic projection called hydrologic rainfall analysis project (HRAP) grid with a spatial resolution of 4 km × 4 km (5,24). The HRAP grid is a coordinate system used for defining individual grid cells. One of the formats in which the NEXRAD rainfall data are archived is a binary format called XMRG (NetCDF is another), which can be converted into ASCII for use in Arc/Info. A program that converts XMRG files to ASCII is available from the NWS (available online from the NWS National Oceanic and Atmospheric Administration [NOAA]). Alternatively, arrangements can be made with the NWS to obtain data in ASCII format.

Measurement of precipitation by radar is influenced by several factors that can be possible sources of error and a few of these factors are briefly described here. Radar reflectivity is converted to rainfall rate using *Z-R* (reflectivity-rainfall rate) relations of the form $Z = aR^b$, where Z and R have units of $mm^6\ m^{-3}$ and $mm\ h^{-1}$, respectively (5,24). The values of the coefficient (a) and exponent (b) can vary depending on the type of storm (e.g., thunderstorm, cold winter rain, and tropical cyclone), but generally the relationship $Z = 300R^{1.4}$ is used by the NWS as a default equation for rainfall measurement (5,24). Variations in rain drop-size distribution (which may vary among different storms) can affect reflectivity (Z), and consequently impact the rainfall rate (24). Another source of error that can affect reflectivity measurement is distance from the radar station. Elevation of the NEXRAD beam increases with increasing distance from the station (5). At long distances, the radar may overshoot precipitation, underestimating (range degradation) the rainfall amount. Conversely, in more arid climates, precipitation below the radar beam may evaporate before it reaches the ground (a phenomenon known as virga) leading to an overestimation. Interference by nontarget objects is another source of error. Objects on the path of the radar beam close to the radar station, when the radar beam is low (known as ground clutter), contaminate reflectivity measurements (2). Reflection from hail is another source of error. As a solid phase, hail generates greater reflectivity than liquid water, thus leading to overestimation (5,21). The NWS makes bias adjustments to correct errors introduced by many of these factors, such as the introduction of filters to correct the effect of ground clutter, mosaicking of several contiguous radars to correct for range degradation, and use of maximum reflectivity threshold (called a hail cap) to prevent rainfall estimates from becoming too large in hail regions of a storm (5,18).

Gauge-based rainfall measurements also have potential sources for error. For example, wind turbulence near the surface and wetting losses on the internal walls of the gauge are the main source of undercatch by a rain gauge (6). Error also can be due to malfunctioning of a tipping-bucket rain gauge caused by biological and mechanical fouling, and in some cases human interference (22). Error in gauge precipitation measurements is generally estimated to be between 5 and 10% (19). Biases in gauge-based precipitation estimates vary with location, season, model type, and height (16). Thus, the quality of rain gauge data depends on how well the gauge is maintained and whether the necessary data bias adjustments are performed.

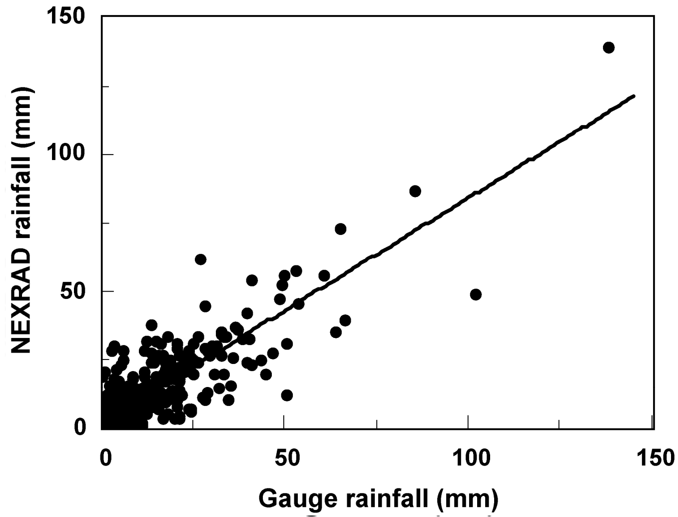

Fig. 2. Relationship between gauge- and NEXRAD-estimated rainfall ($r^2 = 0.76$, $P < 0.0001$, $N = 760$) measured at 15 Texas North Plains Evapo-Transpiration network weather stations in the Texas Panhandle in 2002. The data points represent days in which rainfall was recorded in at least one of the rainfall measurement methods. For the overall stations, the number of days in which precipitation was recorded in at least one of the methods ranged from 34 to 61.

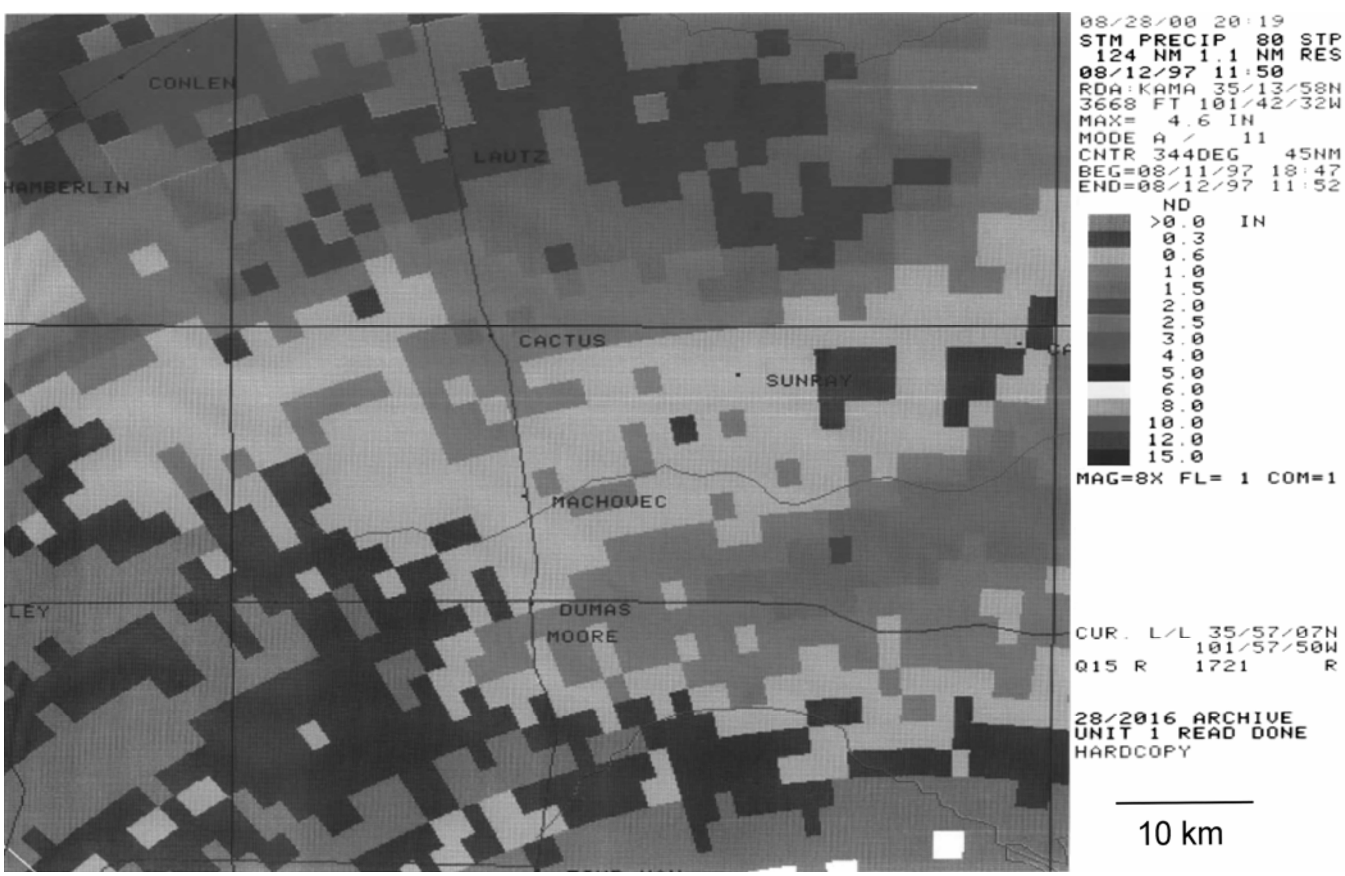

Fig. 1. A NEXRAD image of a rainstorm that passed through the Texas Panhandle on 11 August 1997 depicting pixels of different levels of rainfall accumulation. The radial resolution of the smallest pixel is 2 km.

Furthermore, point rain gauge measurements and radar observations averaged over 4 km^2 areas create a mismatch of sampling volumes between the two methods (22). Because of the above factors and others not described here (5,22), the relationship between radar and gauge rainfall measurements is not straightforward. Comparative studies conducted over the years highlight various ranges of disagreement, with radar often underestimating the amount of precipitation (2,9,10,23). Despite its share of possible sources of error, gauge-measured rainfall estimates are assumed to be the most accurate representation of rainfall amount. Therefore, NEXRAD measurements are compared with real-time gauge measurements for bias adjustments (5).

Figure 2 represents a comparative assessment of gauge and NEXRAD precipitation estimates using 2002 precipitation data. Gauge rainfall data were obtained from 15 Texas North Plains Evapo-Transpiration network stations operated by the Texas Agricultural Experiment Station and spread across the Panhandle. The NEXRAD rainfall data corresponding to each weather station were obtained from the Arkansas-Red Basin (Tulsa, OK) and West Gulf (Fort Worth, TX) River Forecast Centers. The comparison was for days in which rainfall was recorded by at least one of the two measurement methods. Overall there was a good relationship between the methods of measurement ($r^2 = 0.76$, $P < 0.0001$), but a wide variation among stations was observed. The r^2 values for individual stations ranged from 0.44 to 0.97 with a median of 0.77. In many cases, NEXRAD appeared to underestimate precipitation amounts as previously reported (2,9,10,23).

There are many possible sources of error with both radar- and gauge-based precipitation measurements, and thus, perfect congruity is difficult if not impossible to achieve. However, accuracy of NEXRAD rainfall estimates has improved considerably in the last few years with the development of improved radar data processing algorithms, bias adjustment procedures, and introduction of multisensor precipitation estimators (20). This view is supported by a recent long-term comparison (9). The degree of the relationship between the two methods of rainfall measurements varies among locations and regions (9). This appears to be the case in the Texas Panhandle as well, where there was a wide range of variation among the stations.

For many plant diseases, especially those triggered by high relative humidity, the amount of precipitation may not be critical once a threshold humidity level is attained. What may matter the most, rather, may be the frequency and duration of the precipitation even though these too may be loosely related to the amount of rainfall. Thus, above a given threshold, variation between radar- and gauge-measured precipitations may not be a factor for disease development. Hagan et al. (7) and Kemerait et al. (12) used radar precipitation estimates for site-specific application of the AU-Pnut spray advisory program for control of peanut diseases. They reported that the radar-based advisory program produced results comparable to the advisory schedule that utilizes data from an on-site weather station. Relatively speaking, NEXRAD is in its infancy and needs improvement in many areas (21). Deployment of NEXRAD began in the early 1990s and the last such radar system in the United States was deployed in 1997 (21). With the advancement of technology and improvement in precipitation calculation algorithms, there is a potential that NEXRAD can be an effective tool for site-specific disease risk warning in the future, especially for rain- (or high humidity) driven disease epidemics. Its capacity for coverage of a large geographic area, coupled with its high spatial resolution makes it more applicable for regional disease risk assessment than sparsely distributed, point-measured (gauge-based) rainfall.

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