# Crops for a Changing World

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Scientia

# CROPS FOR A CHANGING WORLD

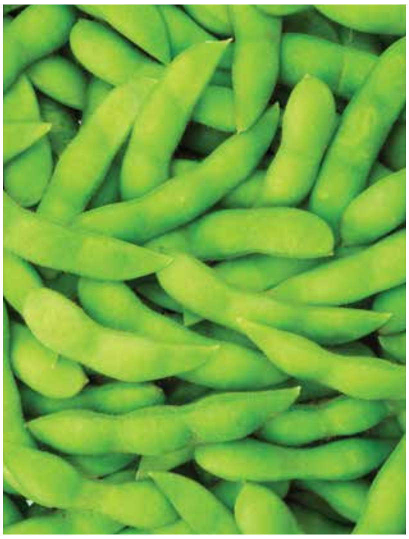
**Professor Robert Aiken, Professor Vara Prasad and Professor Alan Schlegel** at Kansas State University develop new strategies to cultivate some of the world's most important food crops, in order to adapt our agricultural systems to the effects of climate change.

Climate change is expected to dramatically alter global weather patterns, and increase the variability in conditions. This will have detrimental knock-on effects for activities that depend on the climate, such as crop cultivation. Every crop requires its own particular growing conditions, and any change in these could affect productivity. Without appropriate adjustments to cultivation methods, there are concerns that the likely decrease in yield could endanger global food security. The expected changes include higher levels of carbon dioxide, higher temperatures and greater variation in rainfall. Maximising crop yields under these new conditions will require innovative solutions, based on understanding the mechanisms that limit productivity under different climatic conditions.

In this article, we explore the work of three scientists at the forefront of research into the effect of extreme and changing environmental conditions on crop cultivation. Professor Robert Aiken, Professor Vara Prasad and Professor Alan Schlegel work with some of the world's most important food crops – wheat, rice, corn, soybean and sorghum – to develop new strategies for cultivation, which will be vital in the process of adapting agricultural systems to the impacts of climate change.

Their research includes assessing the effects of an array of environmental and management conditions that can affect crop productivity, including increased temperature and carbon dioxide levels, water shortages and different crop rotation strategies, as well as understanding the mechanisms through which these conditions impact crop physiology. Their base at Kansas State University provides the opportunity to conduct field experiments in a state with the largest wheat production in the US. With 40% of Kansas's wheat area semi-arid, it is a particularly suitable location to study mechanisms for improving crop tolerance to drought and heat.

Robert Aiken is Associate Professor and Research Crop Scientist, and focuses on developing management strategies to improve crop tolerance to stress caused by cold, heat or water deficits in semi-arid climates. Vara Prasad, University Distinguished Professor of Crop Ecophysiology, is the director of the Feed the Future Innovation Lab for Collaborative Research on Sustainable Intensification. He is also interested in the mechanisms of crop stress responses, and in developing sustainable crop systems. Alan Schegel, Professor of Agronomy, researches nutrient and water management approaches in dryland and irrigated systems, to identify routes to more efficient cultivation strategies. Their individual research projects interact and inform each other, building on Professors Aiken, Prasad and Schegel's shared expertise in agricultural biology and management, and facilitating their progress in developing resilient approaches to cultivation.



# TOWARDS DROUGHT- AND HEAT-TOLERANT WHEAT

With rising global temperatures, incidences of drought are predicted to become increasingly common, posing challenges to the cultivation of many staple crops, including wheat. **Professor Robert Aiken** is exploring ways to improve crop resilience in the face of these effects.

**Crop Rotations to Combat the Effects of Drought**

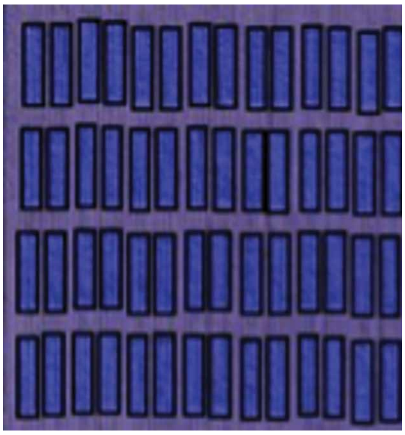
Climate change is expected to lead to higher temperatures and greater variations in weather, which will also increase the risk of drought. Even under current conditions, the supply of water available to crops in semi-arid regions can limit their productivity, and yields in wetter regions can be impacted by drought. The effects of climate change on drought risk are compounded by the constant increase in the global demand for fresh water. Improving the productivity of crops in water-limited regions is essential to meet the world's food requirements against the backdrop of increasingly unpredictable weather conditions.

Regional water availability is also one of the factors that limits the cultivation of wheat, a staple food crop in much of the world. One strategy to improve the efficiency of water use in crops such as wheat is to leave agricultural land fallow in between cropping, which can increase the rate at which the water stored in soil is replenished. However, this recharge is limited due to high losses caused by evaporation. To reduce these water losses in semi-arid regions, continuous crops can be substituted for the fallow period, which permits productive use of water due to plant transpiration. These fallow replacement crops for continuous cultivation can be cover crops, green manure crops or oilseed, grain, cereal or forage. The disadvantage of this approach is that fallow replacement crops can also reduce the soil water available to the following wheat crop, and green manure crops can decrease yields.

Improving wheat yields in water-limited areas could be achieved through understanding the influence of water use on the lower yields obtained in a continuous cropping approach, in relation to wheat grown after a fallow period. This could allow the intensification of cropping without an accompanying loss of productivity. Professor Robert Aiken's research focuses on identifying the factors regulating crop transpiration and its effect on yield in water-limited cropping systems.

Together with his colleagues at Kansas State University, he carried out an experiment to identify the effects of crop sequences and environmental variation on water use and yield in a winter wheat crop in a semi-arid part of Kansas. Between 2002 and 2008, the team cultivated winter wheat in 3-year crop rotations after a feed grain phase and an oilseed crop or fallow phase, under normal growing conditions and drought conditions. The results, published in 2013 in the *Agronomy Journal*, found that an oilseed replacement for fallow (spring canola, soybean or sunflower) had the greatest impact on wheat productivity. This reduced winter wheat biomass, grain yield and the corresponding net economic returns of sowing the wheat crop compared to wheat with fallow, by 18%, 31% and 56%, respectively. This was due to the impacts of the replacement crop on water availability for the wheat.

Under severe drought, the continuous crop had reduced grain yield. The water productivity, or yield relative to water input, was relatively low compared to previously recorded ranges. This suggests that the yield could be improved through management and genetic efforts such as using drought-adapted cultivars. The results indicate the benefits of continuous cropping should be weighed against the impact of reduced water available for subsequent wheat crops.



**Identifying Drought-Tolerant Wheat Through Carbon Isotope Discrimination**

Selective breeding of drought-tolerant wheat varieties is one of the most common approaches to improve the prospects of growing wheat in water-limited regions. Unfortunately, this has proven difficult to achieve in practice, because the relevant traits and their heritability are complex. An alternative method of identifying drought-adapted wheat varieties is through focussing on appropriate physiological traits with high heritability. It has been shown that higher plant transpiration efficiency is associated with lower values of a trait called Carbon Isotope Discrimination (CID), which is a measurement reflecting a process in photosynthesis using the enzyme Rubisco. Carbon dioxide assimilation with Rubisco uses a greater proportion of the $C^{12}$ (the most common isotope of carbon) than $C^{13}$ (a heavier form of carbon, containing an extra neutron).

Plant tissue thus has a higher ratio of $C^{12}$ to $C^{13}$ than the atmosphere, and the CID value is a measurement of this difference. If CID is a suitable indicator for drought tolerance, it should be correlated to grain yield in drought conditions. However, this association varies considerably across different studies, so it could be affected by differences in breeding lines and environmental conditions, such as the water availability.

To try to unravel these interactions, Professor Aiken and his colleagues carried out a study exploring the link between CID and yield in wheat exposed to drought conditions, using 58 different breeding lines in four field trials. Their results, published in *Euphytica* in 2015, found a significant positive correlation in three of the four trials. In the 43 preliminary breeding lines, there was a significant positive association in all three test environments. However, it was weaker in the advanced breeding lines, which were tested in one environment and suffered from winter injury. This may have affected the yield, and hence the CID/yield relationship.

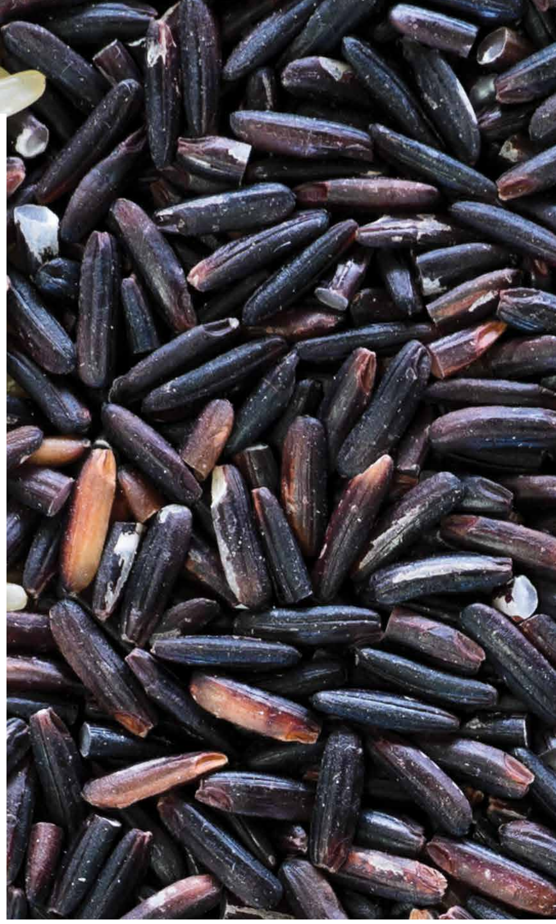
The team also found a significant negative correlation between grain CID and protein content, which could reduce the utility of the wheat for baking. It is possible that this disadvantage could be mitigated by selecting for lines with higher nitrogen uptake and/or utilisation capacity, to improve protein production. Both sets of breeding lines had considerable genetic variation in grain CID, suggesting the potential for selective breeding for the trait. In three of the four environments, the scientists found that grain weight and CID showed a significant positive relationship. These results suggest that grain CID would be a suitable candidate trait to allow the selection of drought-resistant wheat varieties under moderate drought stress. As the positive association between CID and yield was more pronounced in the trial with post-flowering drought stress CID could be particularly relevant as a yield indicator for regions with dry spring conditions.

**Canopy Imaging for Heat Tolerance**

Wheat productivity in semi-arid regions, such as parts of Kansas, is also impacted by high temperatures. High temperatures affect pollination, seed development and canopy productivity, i.e. the plant biomass produced by the utilisation of light in photosynthesis. Like the variation of drought tolerance in wheat, some wheat species have higher heat tolerance. However, both conventional selective breeding approaches and genetic mapping methods require a large number of breeding lines to be assessed, which can be relatively time-consuming and expensive. Professor Aiken and his colleagues are currently testing a new method for detecting heat tolerance, which they hope could improve the speed of identifying heat-tolerant wheat lines. They are carrying out a two-year project in Kansas to explore the potential of predicting the heat tolerance of wheat lines from their canopy productivity. If this proves to be the case, they plan to test whether canopy imaging techniques could enable the rapid, high-throughput screening of wheat fields for heat tolerance. Such a tool would be a great asset to wheat breeders, allowing them to produce new, heat-tolerant wheat varieties, and improve agricultural resilience to high temperatures.

# OPTIMISING YIELDS FOR CHANGING ENVIRONMENTS

In order to adapt to climate change, we need to understand the interactions of altered environmental conditions, including temperature and carbon dioxide levels. **Professor Vara Prasad's** work provides insights into these interactions, and explores management strategies for improving livelihoods in developing countries.



**Elevated Temperatures Impact Rice Yield**

Rice is another crop of huge global importance as a staple food. About 90% of rice cultivation is carried out in tropical regions in Asia, at temperatures close to the optimum for growth – around 30°C. Climate change is predicted to increase temperatures, and measurements in several tropical regions of Asia have shown increases in annual mean maximum and minimum temperatures. Rice yields are known to decline at higher temperatures in the growing season, and rice crops are particularly vulnerable to high temperature damage around the flowering period, as this impacts floret fertility and hence seed set. As rice is such an essential source of food for billions of people, it will be necessary to develop strategies to adapt rice cultivation to higher temperatures. Selective breeding approaches will require the identification of well-adapted varieties.

Professor Vara Prasad is an agronomist at Kansas State University, carrying out research into identifying optimal management strategies for food crops in changing environments. In an article published in 2006 in the journal *Field Crops Research*, Professor Prasad and his colleagues describe their study to identify differences in sensitivity to high temperatures between different rice species and cultivars, through the impacts on spikelet (flower) fertility and grain yield. They used temperature-controlled greenhouses in Gainesville, Florida, to investigate the effect of raising the environmental temperature from 28 to 33°C in 14 cultivars.

Their results showed that higher temperatures significantly decreased fertility and yield in all cases. The cultivar N-22 was the most tolerant, while others were considered either moderately or highly susceptible. However, there were no clear patterns across species (*Oryza sativa* or *glaberrima*), ecotype (*indica* or *japonica*), or origin (temperate or tropical). The main impacts of high temperature on spikelet fertility were through decreased pollen viability, pollen production and reception on the stigma – the female component of the flower. This led to a lower grain numbers and grain yield. Professor Prasad and his team suggest that the next steps for improving heat tolerance are the identification of relevant physiological or genetic traits, and selection for genotypes flowering at earlier times of the day, when temperatures are lower.

**Interactions of Carbon Dioxide and Temperature in Sorghum**

The effect of higher carbon dioxide levels on plant productivity involve many complex, interacting mechanisms. While increased carbon dioxide will negatively affect crop yields through higher global temperatures, it could also enhance plant photosynthetic rates and thus productivity. Despite this, studies of the interaction of elevated carbon dioxide and temperature levels on C3 crops (e.g., wheat, rice, soybean) have shown that the higher growth did not mitigate the damaging effects of high temperatures on yield.

C4 crops such as grain sorghum (*Sorghum bicolor*) are more tolerant of high temperature, and Professor Prasad and his colleagues authored one of the first systematic studies looking at the effects of higher carbon dioxide levels and temperature on their yield. Their results, published in 2006 in *Agricultural and Forest Metereology*, showed that the damaging effects of higher temperatures on pollen viability and grain

yield were increased at elevated carbon dioxide levels. In addition, while elevated carbon dioxide improved sorghum yield at lower temperatures, at higher temperatures it decreased yield. The authors suggest that the impacts of elevated carbon dioxide on fertility are due to its effect in increasing tissue temperatures. Stomatal sensitivity to carbon dioxide may differ between genotypes, which could allow the selection of cultivars with lower sensitivity and thus a smaller increase in leaf temperature. Similarly, genotypes may also vary in the response to floret fertility under high temperatures and can be used in breeding programs to enhance tolerance to higher temperature stress.

**Advances in Heat Tolerance**

Understanding the mechanisms of heat tolerance in crops is still a pressing issue. In a recent review article in *Field Crops Research in 2017*, Professor Prasad and his colleagues discuss the current state of knowledge in this area. Work over the last decade has led to the identification of the specific optimum and damaging temperatures of many important food crops. It has also become clear that high night-time temperatures often have significant impacts on grain yield and quality.

In rice, mechanisms to avoid heat damage have been discovered, although these remain elusive in other crops. Improving crop resilience to high temperatures could build on these insights from rice, using physiological, genetic or molecular approaches. However, targeting these efficiently will require identifying the sensitivity of each stage of the vulnerable reproductive phase, preferably on a scale of hours.

Rice has also provided an example of the great value of crop wild relatives as a source of novel traits, including resistance to high temperatures. The early morning flowering trait has been systematically identified and, with new molecular tools, incorporated into popular cultivars. Similar approaches could be used in wheat, and wild varieties are known to have considerable gene-associated variation in heat tolerance. New technologies have also increased the scope and ease of phenotyping (i.e., measurement of plant traits), and promising methods include the development of molecular biomarkers through 'omics' approaches such as lipidomics or metabolomics (i.e., measurement of lipids or metabolites). Another approach is the use of sensors to enable field-based high-throughput phenotyping, which is currently being tested by Professor Robert Aiken and his colleagues.

**Management Strategies for Global Solutions**

While these new methods promise exciting improvements in productivity, there is still considerable scope to boost yields through optimising traditional cultivation techniques, especially in developing countries. Professor Prasad is particularly interested in the application of innovative farming systems research to improving livelihoods of smallholder farmers. He recently became the Director of the Feed the Future Innovation Lab for Collaborative Research on Sustainable Intensification (SIIL) at KSU, which explores routes to increase agricultural productivity and income for smallholder farmers in Africa and Asia. Supported by USAID, the SIIL goals are reducing global hunger and poverty.

Together with research through multiple Innovation Labs in collaboration with the Savanna Agricultural Research Institute in Ghana, Professor Prasad and his team developed several improved agricultural practices to enhance productivity in West Africa. They assessed the impacts of conservation methods of cultivation on crop productivity and soil health – these methods include the use of crop rotations, crop residues, cover crops, minimum or no tillage, nutrient management and water harvesting. One of their recent projects focussed on maize and soybean cultivation in Ghana, and sorghum, millet, cowpea and peanut in Mali. The team showed that minimum tillage produced the same yields as conventional tillage, while saving on labour costs. Inorganic fertiliser and planting maize on tied ridges rather than in flat beds improved yield. Application of inorganic phosphorus fertiliser increased yield of soybean, cowpea and groundnuts.

Professor Prasad and his team are continuing their research on improving farming systems focused on yield improvement and efficient use of resources in multiple countries in Asia and Africa, and hope that their findings can be extended from the local experimental level to the wider regions, leading to larger-scale, sustained benefits in agricultural productivity.

# CROP YIELD AND PROFITABILITY IN WATER-LIMITED CONDITIONS

Restricted water availability can determine yields and change the profitability of growing comparable crops. **Professor Alan Schlegel** compares the effects of different agricultural practices on yields in limited-irrigation and dryland crop systems.

**Irrigation Levels Affect Relative Crop Profitability**

One of the challenges facing agriculture as a result of increasing intensification and population density is the greater pressure on groundwater supplies. Climate change will also affect this, through increasing the unpredictability of rainfall and hence the recharge rates of groundwater. In the west-central areas of the Great Plains in the US, covering parts of Kansas, Nebraska and Colorado, the main source of irrigation water for agriculture is the Ogallala aquifer. This system is currently over-exploited and supplies declining volumes of water. Maintaining crop yields in this region will require improving the efficiency of water use in agriculture, and, with global freshwater supplies under pressure, insights gained from research here could be applied to other areas.

As the availability of water for irrigation decreases, farmers may consider applying lower levels of irrigation to their crops. Certain crops are less affected by water scarcity, and may become more appropriate to the new conditions. However, the decision to plant a particular crop is influenced by its profitability, which depends on its market value as well as its yield. Understanding how the profitability of common crops changes under different irrigation conditions is important to inform crop choice and higher-level planning to regulate water and food supplies.

Professor Alan Schlegel and his team at Kansas State University carried out a study to compare the yield and profitability of four common Great Plains crops under three different irrigation scenarios – of 127, 254 and 381 mm of irrigation water annually. These crops – corn, grain sorghum, soybean and sunflower – are all grown in the summer and compete for farmers' resources. The results of the study, published in 2016 in the *Agronomy Journal*, show that while corn is the most profitable crop at higher irrigation levels, its profitability advantage is lost at lower levels. However, its yield by grain weight per area exceeded that of sorghum, soybean and sunflower at all irrigation levels.

Local crop selling prices will determine the profitability under different irrigation scenarios, and this study was based on prices in Kansas. The team's work also sheds light on the circumstances under which there are economic grounds for increasing irrigation. Corn yields increased with all irrigation increments. For soybean, it was profitable to increase irrigation to 381 mm, but to a lesser extent than corn. For sorghum and sunflower, irrigation beyond 254 mm was not profitable. Although the estimates of profitability will vary depending on input costs and sale prices, the differences in irrigation profitability for corn and soybean, compared to sorghum and sunflower, are in line with the results of previous studies.

**Limited Irrigation May Favour Continuous Corn Monocultures**

Another piece in the puzzle of improving crop productivity in irrigation-limited conditions is the role of crop rotation. This is an ancient practice that may increase yields through a variety of mechanisms, including improving soil structure, reducing weed numbers, enriching soil nitrogen levels and others. Most research on crop rotations has focussed on maximising yield under rainfed conditions. There is less guidance available for farmers on which crop sequences are most suited to limited-irrigation conditions, such as those common in the central Great Plains.

Professor Schlegel and his colleagues performed an experiment to fill this gap, comparing the yields and profitability of corn

grown in three different crop rotations, or continuous corn. Published in the *Agronomy Journal* in 2016, their results demonstrate that while the continuous corn rotation had lower relative yields in comparison to the corn in the diverse rotations, its yield over the whole rotation cycle was greater. Using the local price for the four crops and the cost of production of the four cropping systems, continuous corn was the most profitable.

The relatively lower yield of the corn cycle in the continuous rotation was considered a consequence of the higher water use of corn compared to the other crops, which affected grain development. This shows that continuous monocultures may be the agricultural system preferred by farmers under limited irrigation scenarios, as profitability is often the main criteria in determining agricultural practices. However, the process of improving resilience to climate change should also consider environmental impacts and integrate their value into production systems in order to avoid decision-making based on short-term, economic gains.

**The Role of Rotation Length in Wheat Yield**

Planting crops in diverse rotations also has great potential to sustainably improve yields in dryland regions that rely on rainfall. In the Great Plains, the most common dryland wheat rotation used to be a two-year wheat-fallow system. However, replacing the fallow with another crop may lead to more efficient use of land and water inputs. Advances in available resources, such as improved herbicides, mean that it is now possible to plant wheat in rotation with warm-season crops such as sorghum or corn. The most popular rotation in the central Great Plains is now a three-year cycle with wheat, a warm season crop and fallow (WSF). Alternative rotations are also used, and longer rotations with two instead of one year of certain crops may offer benefits in terms of yield, profitability and lower required inputs.

Professor Schlegel and his colleagues conducted one of the first long-term studies of the yield of two four-year wheat rotation systems, as well as their water use and water productivity, compared to those of continuous wheat (WW) and of the popular three-year WSF rotation. The two mixed rotations were wheat-wheat-sorghum-fallow (WWSF), and wheat-sorghum-sorghum-fallow (WSSF), and the study was conducted from 1996 through 2015. Their results, published in 2017 in the *Agronomy Journal*, show that growing wheat in rotation with sorghum and fallow increased the overall grain yield relative to continuous wheat.

Wheat grown after fallow, and sorghum grown after wheat, led to higher grain yields, crop biomass, soil water and water productivity than wheat grown after wheat or sorghum grown after sorghum. However, the four-year rotations had similar profitability to those extrapolated for the three-year WSF rotation, so increasing the intensity of cropping does not automatically increase profitability. The relative water use by different crops in rotations affects the yield throughout the rotation cycle, and should be considered in planting decisions together with the yield potential and market value.

# Meet the researchers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Professor Robert Aiken received a PhD in Soil Biophysics at Michigan State University in 1992, as a USDA Water Science Fellow at the Department of Crop and Soil Sciences. He then worked as Post-Doctoral Soil Scientist in the USDA/ARS Great Plains Systems Research Unit in Colorado, before moving to the USDA/ARS Central Great Plains Research Station in 1995. Since 1998, he has worked as Research Crop Scientist at the Kansas State University Northwest Research-Extension Center, and is also Associate Professor. He also advises the Central High Plains Working Group, the North Central Regional Committee 1200 Regulation of Photosynthetic Processes and the Sunflower Crop Germplasm Committee.

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Professor P. V. Vara Prasad obtained his PhD in Crop Physiology from the University of Reading in 1999. From 2000 to 2005 he worked as Postdoctoral Research Associate in the Agronomy department of the University of Florida. He then moved to Kansas State University to take up the role of Assistant Professor in Crop Ecophysiology, becoming Associate Professor and Director of the Centre for Sorghum Improvement in 2009. In 2013 he became Professor of Crop Ecophysiology, and in 2014 he also became Director of the USAID Feed the Future Innovation Lab for Collaborative Research on Sustainable Intensification, both at Kansas State University. In 2016, he became University Distinguished Professor a lifetime title that represents the highest honor KSU can bestow on its faculty.

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Professor Alan Schlegel received his PhD in Soil Microbiology/Fertility from Purdue University in 1985. In 1986, he became Assistant Professor at the Kansas State University Southwest Research-Extension Center at Tribune, KS. In 1992, he accepted the position of Associate Professor at the Center, and in 1998 he became Professor. His other professional activities have included work with the Certified Crop Advisor program, Soil Science Society of America, and the American Society of Agronomy, for which he is currently serving as a Board Representative.

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