1.2 FORTY YEARS OF FIGURING, FINDING, AND FINESSE

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1. INTRODUCTION

Professor John Norman has had a long and fruitful history of instrumentation development. A list of the devices he has had a hand in would include

- Quantum sensor (Norman et al, 1969)
- Various traversing devices for measuring sunflecks in canopies (Miller and Norman, 1971; Perry et al, 1988; Norman and Jarvis, 1974)
- Drag anemometer for turbulence measurements (Norman et al, 1976; Perry et al, 1978)
- An aerosol sampler (Pena et al, 1977)
- A real time computer graphics system for forecasting (Cahir et al, 1981)
- Microlysimeter for measuring ET and drainage (Cook and Norman, 1982)
- Root length measuring device (Wilhelm et al, 1983)
- DEMON, the CSIRO leaf area index instrument (Lang, A.R.G., X. Yuegin, and J.M. Norman, 1985.)
- A portable CO_2 calibration device (LI-COR literature)
- A jig for measuring bidirectional reflectance from leaves (Norman et al, 1985)
- The "pine cone" sensor, a device for measuring the angular distribution of diffuse radiation above and within canopies (Hutchison et al, 1986)
- Lighted bar or light-pipe used at night in turf (Kopec et al., 1987)
- A field portable photosynthesis system (McDermitt et al.1989)
- LAI-2000 leaf area index instrument (Welles and Norman, 1991)
- Soil respiration chamber (Norman et al, 1992)
- A device for measuring directional emissivity (Norman et al, 1994)
- Heated needle anemometer (Bland et al, 1995)
- Multiband vegetation imager (Kucharik et al, 1997)
- Equilibrium tension lysimeter (Brye et al, 1998)
- A high precision infrared radiometer (Baker and Norman, 1999)
- A soil and topography mapper (Zhu, Morgan, Norman, Yue, and Lowery, 2004)
- A device for measuring runoff (Bonilla et al. 2006)

My purpose for this paper is to look at a couple of the these devises from the early part of John's career, and share the story of how they came about.

2. EARLY IMPRESSIONS

In 1973 I transferred to Penn State as a third year undergraduate to study meteorology. I had no idea what a meteorology department would look like, and as I became familiar with Penn State's, it became clear that there was one faculty member that was a little different from the rest. He was a new hire, his Ph.D. was in soil science, his professional interests were centered on plants and soils, and his name was Dr. Norman. I had never heard of micrometeorology before, but Penn State had a group that did it, including Dr. Dennis Thomson, Dr. Hans Panofsky, and now Dr. Norman. It was my impression at the time that much of meteorology was modeling, not measurements. Real world data was something that appeared magically at 00Z and 12Z each day, at least for the synopticians. In Dr. Norman's world however, real data was something you went out and measured yourself. His students were working with devices that they often had to build and calibrate themselves, and sometimes those measurements required the use of a big trailer containing a computer and tape drive. Thus, my first impression was that Dr. Norman was someone to avoid.

When I became a graduate student, the first order of business was to find a thesis advisor, and the first step in doing that was to find out from older students which professors were the best ones to work with. Thus, I found myself in Dr. Norman's office listening to the scope of topics that I might be involved in. One caught my interest, and my fate was sealed.

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The topic that caught my interest was radiation transfer through plant canopies, but that's not how Dr. Norman described it. What he described was a practical problem of how to best use fuel oil -fired heaters for frost protection in an orchard. A fundamental piece of the puzzle was predicting the view that branches and blossoms would have of the heaters, the soil, and the sky. It all seemed to come down to algebra and geometry. At the time John was doing several joint projects with Prof. J. D. Martsolf in Penn State's Dept. of Horticulture, so this was not just theory, there were real orchards involved (Figure 1). I had grown up on a farm that had at one time included a commercial orchard, I liked apples, and I could do algebra, so it was a natural fit.

Figure 1: One of Penn States orchards maintained by the Department of Horticulture. Several heaters can be seen.

Working with John was - as promised - a delight. He was helpful and encouraging, he made you think, and stretch and achieve more than you thought you could. When you ran into a dead end, he was a fount of creative suggestions. There was a downside to having him as an advisor, however, and that was the competition. You always knew he was in his office by the long line of students in the hall waiting their turn with him. Once you made it into his office, there were the phone calls. I spent many hours sitting there, waiting while John interacted with colleagues from across campus or across the country. I learned quite a bit from that waiting, besides patience. I began to learn the who's who of micrometeorology, and what sorts of things they were doing. I also began to realize that John knew no boundaries; he interacted with people from all sorts of disciplines, and was constantly learning and applying new things. Above all, I learned not be afraid to ask simple, basic questions that revealed your ignorance. John did that all the time, and it worked very well for him.

Figure 2: John Norman, circa 1977, getting photographic documentation in an orchard.

In the late '70's, John began talking about a move the University of Nebraska. He suggested I might do likewise and finish my Ph.D. out there. I was not excited by that prospect, but he kindly paid for me to accompany him and his wife Jane for his interview in Lincoln, to let me check the place out. It went agreeably for all of us, and by the Autumn of 1978, we were Nebraska residents.

This was a very interesting time, since we were both starting at a new place, and I got to observe John Norman in action nearly all day every day. We were in a large and diverse Agronomy department, and within that, John was part of the Sorghum Physiology group, along with Jerry Easton, Jerry Maranville, Max Clegg, Charlie Sullivan, and others. John was keenly interested in understanding and modeling soil-plant-atmosphere interactions, and he was now surrounded by people with expertise in many of the relevant processes. He spent a lot of time asking questions and absorbing answers, from people all across the university. John was the proverbial kid in a candy store.

3. POROMETRY

Lincoln, Nebraska was also the home of a small company named LI-COR. John and I had visited them during the interview trip, and met the owner Bill Biggs who, I discovered, shared John's interest in quantum sensors. LI-COR also had made a series of porometers over the years (LI-60, LI-65), and was working on something called a steady state porometer. John was interested in porometers, since that was how you could tell what stomates where doing, and had purchased a Delta-T Mark II porometer with some of his start-up money. It wasn't long before John was working with LI-COR to do a formal comparison of all of these porometers (Figure 3).

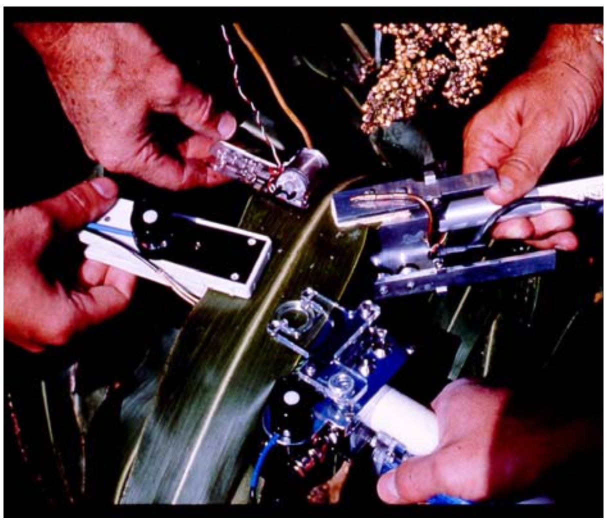

Figure 3: The porometer comparison conducted by John Norman. Shown are the LI-COR LI-65 (upper left), Delta T Mark II (lower left), a Kaufman convective chamber porometer (upper right), and the LI-COR LI-1600 steady state porometer (lower right)

The results of the comparison (Figure 4) showed good agreement between the LI-1600 and the Delta T, but also clearly showed that the LI-65 had problems. As a result, LI-COR discontinued its production. Interestingly, this move met with customer resistance, since many liked the low price, and didn't mind the uncertain results.

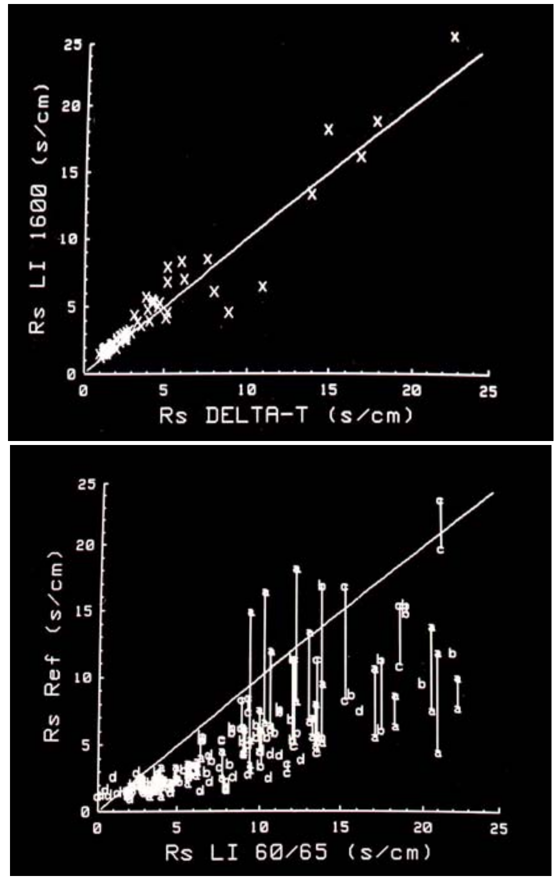

Figure 4: (Top) Comparison between the Delta T and LI-1600 porometers. (Bottom) The LI-65 had problems, and LI-COR discontinued production.

4. PORTABLE PHOTOSYNTHESIS

At about this time researchers (e.g. Farquhar et al, 1980) began to demonstrate the role that leaf photosynthesis plays in stomatal behavior, and it became clear to John that simple porometer measurements would never be sufficient in understanding stomatal function. Charlie Sullivan had been using a field technique involving large chambers and syringes to estimate carbon uptake in the field. The plant part to be measured was enclosed in a clear plastic chamber, and two syringes of air were extracted a fixed time apart. The air in the syringes was measured later by injecting them into a CO_2 analyzer back in the lab. John adapted this technique by adding mixing fans to the chamber to minimize boundary layer resistance, and by making porometer measurements before and after the CO_2 measurement (Figure 5).

Figure 5: John Norman (right) making "simultaneous" measurements of stomatal conductance and photosynthesis, using a Delta T porometer, and a home-made chamber with syringes.

The next innovation came by putting the sensor head of the LI-1600 porometer into the leaf chamber so that stomatal conductance could be measured during the period when the syringes were extracted (Figure 6). This was no longer a steady state conductance measurement, but a closed-system transient, whereby the conductance is computed from the rate of change of water vapor with time.

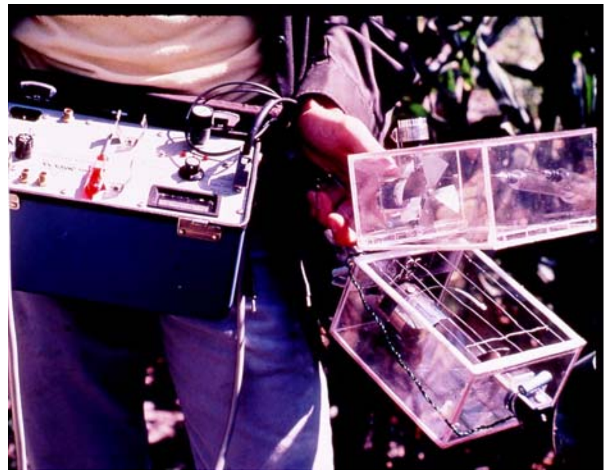

Figure 6: LI-1600 steady state porometer modified to measure humidity in a leaf chamber equipped with CO_2 syringes, barely visible on the right.

A major breakthrough came when John came across a company named Liston-Edwards in Newport Beach, California, that made a CO_2 gas analyzer that was small enough to be portable, low power enough to be run by a battery, and with specifications that could be suitable for leaf photosynthesis measurements. John obtained a sample, and went to work adapting it for his purposes. The result was a John Norman classic: a portable field photosynthesis system in five pieces (Figure 7).

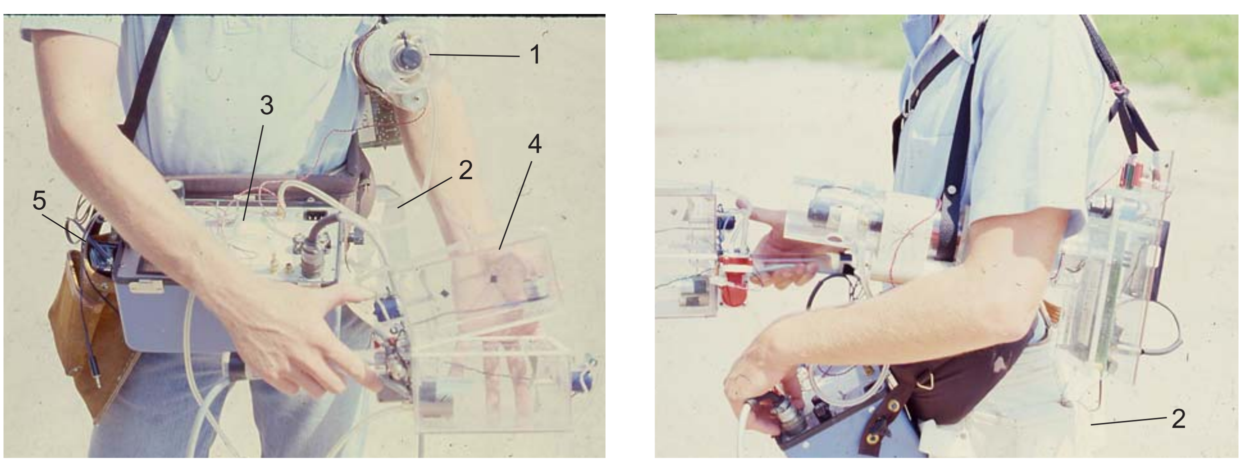

Figure 7: A field portable photosynthesis system in five pieces: 1) Liston-Edwards gas analyzer optical bench and board; 2) the analyzer power supply; 3) LI-1600 console; 4) Leaf chamber; 5) Tape recorder for data logging.

To make a practical photosynthesis instrument would require help, so John tried to interest LI-COR in taking this system on as a product. Bill Biggs was initially reluctant for two reasons: 1) it was a transient system, and after the difficulties with the transient LI-65, Bill was definitely in the steady state camp. 2) it would be expensive, and the market size was a real guess, since nothing like John's five piece system had ever been commercialized before. Eventually, LI-COR took on the project, and in the first prototype, the unit consisted of three pieces, two worn around the waist, with the gas analyzer optical bench inside of a very large chamber handle (Figure 8).

Figure 8: The first prototype of LI-COR's implementation of John's photosynthesis system had the IRGA in the handle.

The final configuration moved the entire IRGA to its own box beneath the control console, and the LI-6000 Portable Photosynthesis System was born. Best of all, there was no more tape recorder; the console did all the calculations on the spot, so for the first time, it was possible to see simultaneous conductance and photosynthetic values right in the field.

Being a good student of Champ Tanner, John understood the importance of sensor calibration, and this included his photosynthesis system. Calibrating a photosynthesis system meant calibrating the CO_2 analyzer, and that typically involved two steps: zeroing (making it read zero with no CO_2 present), and spanning (making it read a known concentration correctly). Zeroing in the field was not hard, as CO_2-free air could be obtained with a chemical scrub tube. Setting the span was another issue, as taking a tank of compressed gas to the field usually problematic. John came up with a device that could solve the problem, by mixing pure CO_2 as measured in a microliter syringe with a liter of CO_2 free air. Figure 9 shows his original sketch.

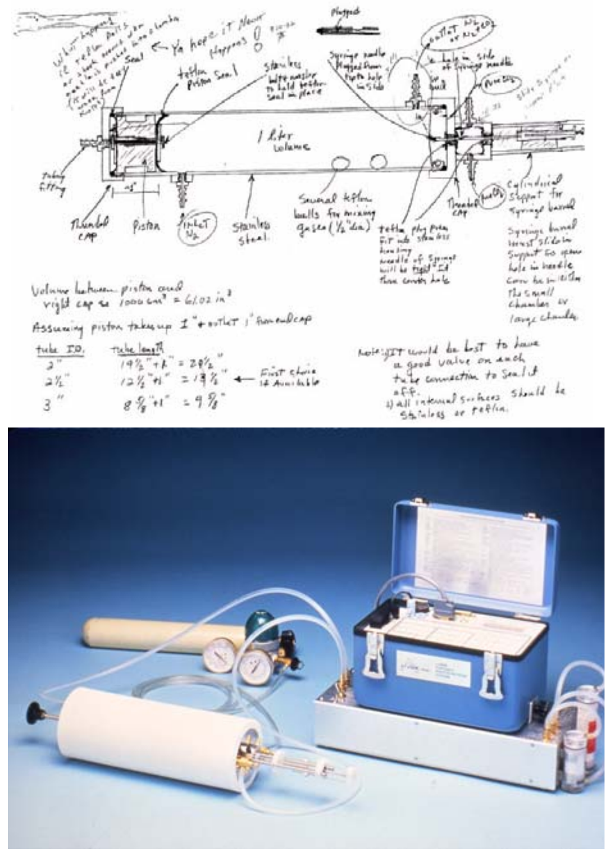

Figure 9: John's original sketch of his mixing cylinder for calibrating the IRGA, along with the final embodiment of it and the LI-6000 Photosynthesis System

The LI-6000 started LI-COR started down the path of portable photosynthesis systems, and was followed by the LI-6200 with a LI-COR-build gas analyzer, and then the LI-6400, which is a steady state system with the gas analyzers built into the leaf chamber.

5. CANOPY STRUCTURE

John's dissertation and post-doctoral work was heavily involved with radiation transfer through plant canopies. This topic formed an integral part of his modeling work, providing the framework on which to add physiological responses and atmospheric processes. Forward modeling, that is, predicting light penetration given the canopy properties, was relatively straight-forward. There was, however, the intriguing notion of inverting the model. That is, make some radiation measurements from which the canopy properties could be computed. But, what model to invert, and what parameters to measure?

5.1. MODEL TRAINS

One approach was to measure sunflecks, the fraction of area under a canopy that is sunlit. Measuring this value at several sun angles produces a series of equations with nearly as many equations as unknowns, yielding hope for a numerical solution. John began exploring this approach while at Penn State and continued at Nebraska. We built a traversing system using HO scale model railroad equipment (Figure 10). The track lay in 30 feet of aluminum U-channel. One of the cars on the train contained a light sensor and two circuits: one accumulated charge all the time, the other only when the signal from the sensor was above some threshold value. Pulling the train was a very nice model of a Heisler geared logging locomotive. The measurement consisted of sending the train down and back, measuring the charge on the two circuits, and ratioing them to yield sunfleck fraction for that sun angle. This would be repeated over the course of a half-day to cover a range of sun angles. Why a model train? In retrospect, I think it was largely a scheme on John's part to get his model railroad fanatical student (me) out of the lab and into the field.

5.2. PINE CONE SENSOR

Another approach was to look at how the distribution of diffuse radiation changes with angle as one got deeper and deeper under a plant canopy. John knew from modeling that there is a pronounced affect, but the problem was how to measure this distribution of radiation. While at Penn State he hit upon an idea for a sensor which, given its shape, came to be known as the Pine Cone Sensor (Figures 11, 14, and 16). It consists of a stack of photodiodes in a diffusing column, with each segment of the column separated from the others by fins. Thus, each photodiode is exposed to a different angular ring of the sky above. He found a machine shop to take on the task before he left Penn State, and took delivery of the result in Nebraska.

Inverting Pine Cone data consisted of running a forward model to predict diffuse distributions under a range of leaf area indices, then finding the one that came closest to matching the measured distribution.

Figure 10: Sunflecks measured with a model train. The locomotive had to be "streamlined" a bit to prevent snagging foliage.

Figure 11: the Pine Cone Sensor shown with a Campbell Data Logger. When used in direct sun, it had a shadow band, shown on the right.

5.3. DEMON

In 1983, John took a three month leave to visit Canberra, Australia. He took along his Pine Cone Sensor, and his algorithms for inverting sunfleck data. While there he spent some time with Dick Lang who was looking for one more project to work on before he retired. Dick got very interested in the inversion problem, and went to work studying what John had done so far. They came up with the idea for a simple, hand held threshold detector, not unlike the one on the model train back in Nebraska. The canopies of interest now were large trees, not crops, so carrying the sensor was an option. A sighting device was added so the operator could keep the sensor aimed at the sun while walking. Eventually, this device became a commercial product, marketed under the name DEMON (Figure 12). Dick Lang did a lot of pioneering work as part of his “final project”. He unearthed an analytical solution to the sunfleck inversion problem that made the solution very simple (Lang 1987). He figured out how to deal with gaps in the canopy, such as caused by rows, in a rigorous fashion (Lang and Xiang 1986). And he deduced from Cauchy Theorems that indirect techniques for determining canopy structure were in fact computing one half of the surface area of the foliage, instead of a projected area (Lang 1991).

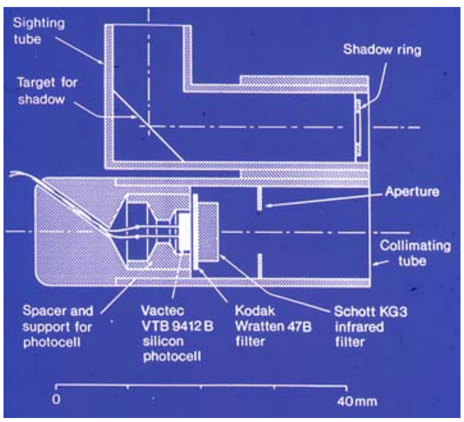

Figure 12: A schematic of the DEMON sensor for measuring sunfleck fraction. The sun would be to the right.

5.4. SEARCHING FOR THE LAI-2000

LI-COR was interested in developing some sort of canopy structure sensor. The model train approach did not seem viable, and was quickly ruled out. It was the mid-80s however, and the idea of using a digital camera with a fisheye lens to do canopy structure work started to seem a possibility, and John spend a month working with LI-COR one summer investigating that approach. We put an IBM PC with a Frame-Grabber card in Bill Bigg’s van, and attached it to a camera. Power came from a portable generator. We used visible and far-red filters, looked down on short canopies, up through taller canopies, and collected data in a variety of settings. Unfortunately, all data and photos from that experiment are long gone, save one fisheye near infra-red photo of a row of corn (Figure 13). The conclusion of the work was that it was a viable method, but the technology was not there yet for an inexpensive field portable instrument.

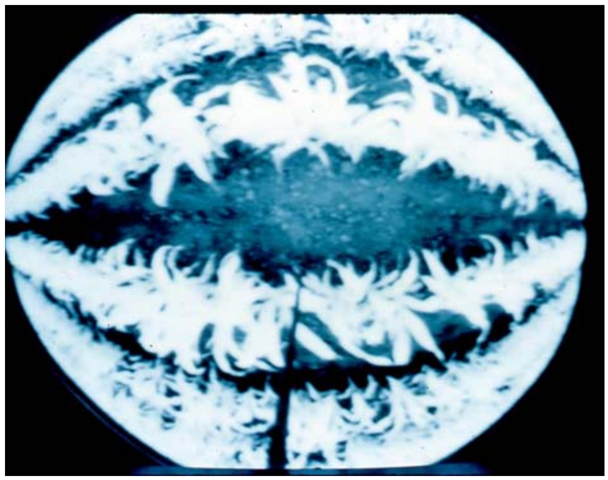

Figure 13: A near IR hemispherical photo looking down at corn. The idea was to try a gap fraction inversion based on the dark soil and bright leaves.

The Pine Cone Sensor also seemed a possible way to proceed, and was seriously considered, as evidenced from the “brochure picture” in Figure 14.

Figure 14: The product that never was. A data logger, based on HP-IL interface, with two Pine Cone Sensors (large and small) attached.

Champ Tanner had meanwhile miniaturized the Pine Cone, and improved its angular response. All that was missing was a robust, practical, inversion algorithm, and we put a fair amount of effort into finding such a thing. Figure 15 illustrates typical results when comparing inverted LAI with direct measurements in corn. Finally, and perhaps out of desperation, we tried treating the Pine Cone data as if it were a direct beam transmittance, and inverting it using a gap fraction analysis. There was good reason to not try this sooner: much of the radiation seen by the sensor beneath the canopy is scattered, so simply ratioing above and below readings would significantly overestimate gap fractions. Surprisingly, applying the sunfleck analysis to the corn data yielded much less scatter in the comparison, and nearly followed the result predicted by the model.

Now the question became, how to optimize the Pine Cone Sensor for sunfleck measurements? Several ideas were considered until one day Lyle Middendorf, a LI-COR engineer, happened to notice a display of door peep-hole viewers while in a hardware store. This miniature lens idea led to the final embodiment of the LAI-2000 as a fisheye device with a detector partitioned into five concentric rings (Figure 16).

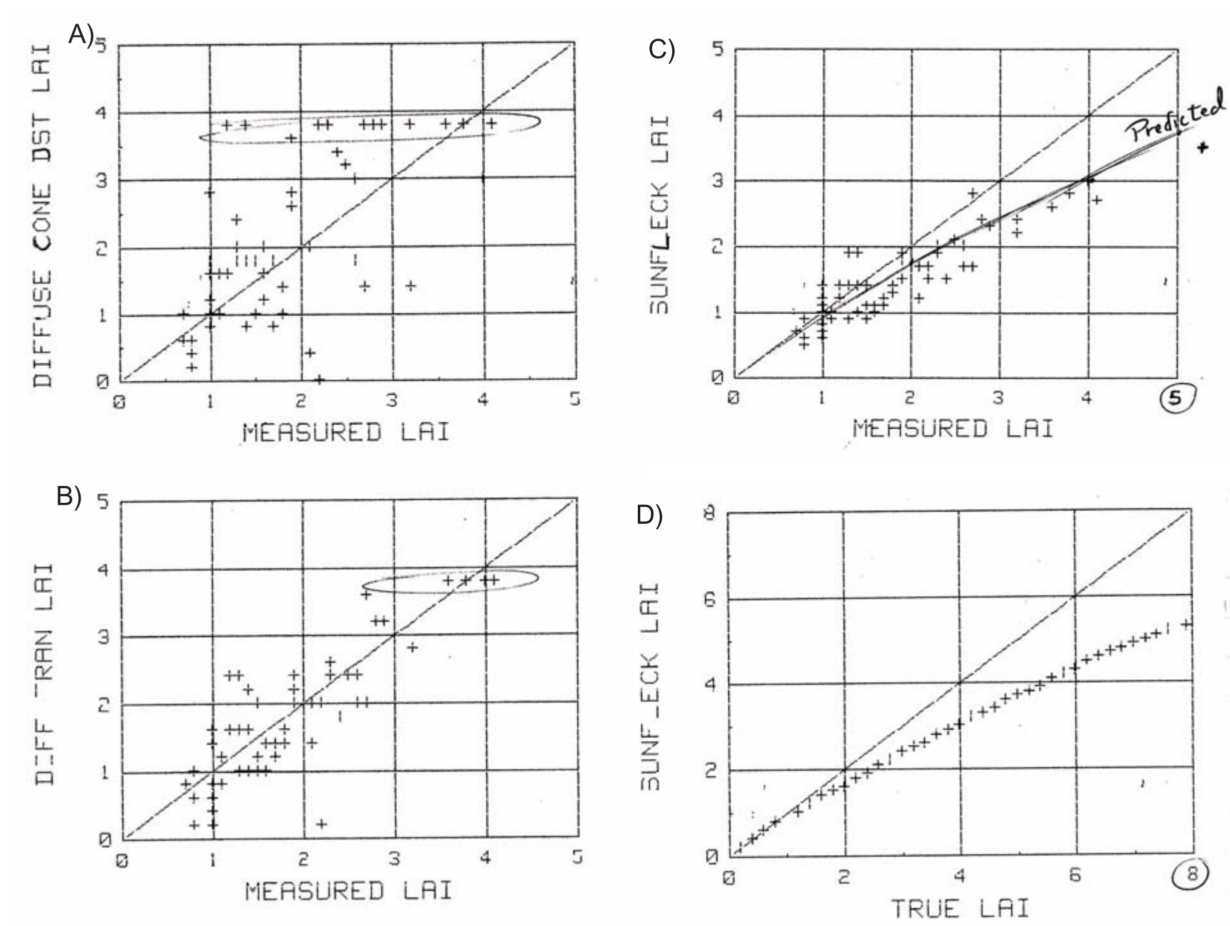

Figure 15: Three of many attempts to relate Pine Cone sensor output to Leaf Area Index. A) LAI inverted from the measured diffuse distribution compared with directly measured LAI. The model didn't consider LAI values greater than 3.8, hence the cluster of circled points. B) LAI inverted from a simple integrated diffuse transmittance reduced the scatter somewhat. C) LAI inverted from a gap-fraction treatment of the data has the lowest scatter. The hand drawn curve labelled "Predicted" comes from D), a theoretical treatment for how the Pine Cone sensor would overestimate sunflecks in this particular canopy, based on the measured spectral properties of the leaves. This data is for corn. (Scans from the author's 1986 notebook)

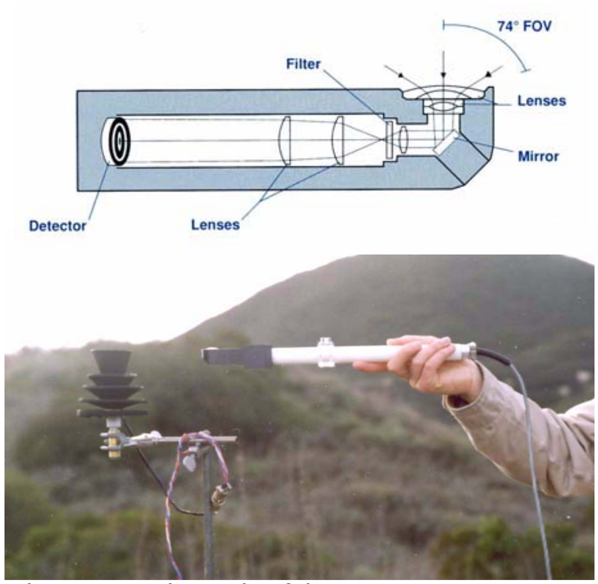

Figure 16: Schematic of the LAI-2000 sensor head, and a prototype of the instrument being tested with the Pine Cone sensor.

6. Conclusion

In 1988 John Norman moved back to the University of Wisconsin to replace his retiring mentor, Champ Tanner. There, John has continued to use his creative drive and curiosity to solve measurement problems, and create tools and ideas. A few of the devices turned out to be stunning successes, used by scientists all over the world. Others inventions served their purpose, and are all but forgotten.

Of far greater importance to John, however, are the students and colleagues he has shared life with during his stays in Pennsylvania, Nebraska, and Wisconsin, and the countless others he has touched around the world. His forty year career is the true stunning success, and we are all the better for it.

Thank you, John.

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