Scientific Measurements: Better Counts, Measurements, Science, and Decisions

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The word *science* comes from a Latin word for knowledge. We build knowledge by making observations. We can make better contributions to this knowledge base we call science by making careful observations that incorporate measurements and experiments. The simplest observations, called qualitative observations, may tell us what is, versus what is not. Qualitative observations are a start, but we can do better.

This article encourages more care when recording bird count numbers. By understanding the technical ways that scientists use numbers to indicate levels of significance in their data, birders will be able to increase the value of their birding data to scientists and maximize their contributions to science.

QUALITATIVE VERSUS QUANTITATIVE OBSERVATIONS

Qualitative (non-quantified) observations are often a precursor that can lead to identifying phenomena worthy of deeper investigation. You might notice that summers are hotter or longer or that birds, bees, or butterflies are absent when they should be plentiful. You may wish to go deeper into understanding the underlying causes and the relationships between them. You may wonder about the magnitude and the causes of the qualitative changes that you notice. To do so requires quantitative measurements for several important reasons.

Quantitative measurements should be reproducible by future researchers within the uncertainties of the observation and thereby provide a starting point for discussions of possible causes and, more importantly, possible solutions to perceived problems. Human activity is increasingly encroaching on the natural world and the earlier we identify a problem the easier it may be to solve. Science has given us measuring instruments that are incredibly sensitive to almost any type of chemical or physical variable applied at the local or the global level, so that correlations can be ascertained among measured physical variables, including bird populations.

WHICH NUMBERS COUNT?

Almost all quantitative measurements involve counting something. This part of the scientific process can be as simple as visually counting sheep or birds in a flock, or as complicated as counting gravitons or proton decay products using extremely sophisticated detectors. A count results in a number that contains three pieces of information: magnitude, precision, and the unit of measurement. We address magnitude and precision for bird counts, but the lessons apply to most counted observations in the natural world. A better understanding of how numbers convey information about magnitude, precision, and unit of measurement will allow birders to record more and better information, so their data will best contribute to possible future use in more rigorous scientific analyses.

Key Terms and Concepts

Magnitude. Magnitude is a measure of size, extent, quantity, or amount of a physical variable. In bird counts it is, most commonly, flock size or the number of birds counted. It could also apply to any measurement (e.g., velocity, distance and height flown, number of feeding trips, or quantity of food items brought).

Precision. Precision indicates how repeatable a measurement is. Do you get the same measure or the same count each time you counted the same thing? Scientists indicate this in the special way that they write the numbers for the magnitude. Some would say that precision is how fine your measurement is. In target shooting, precision is how close the shots are, not to the bullseye, but how close they are to each other, sometimes called a grouping. Figure 1 illustrates the concepts of accuracy and precision for the target shooting example.

By saying that precision is a measure of fineness, we mean that measuring to the nearest whole number is finer or is a more precise measure than is measuring to the nearest ten, which is more precise than measuring to the nearest hundred. By repeatability, we mean that a more precise measure will vary less when remeasured than will a less precise measure. This precision is shown by the position of the least significant digit, or significant figure (hereafter referred to as a *sig fig*). A number that has a least sig fig in the ones place is more precise than one with a least sig fig in the tens place. The right-most or least significant digit in a number, which is the one that determines its precision, is often shown by placing a line or bar above it, or below it, such as the 5 in the number $2\underline{5}0$. (The line above the least sig fig is the more frequently seen convention, but in this article the limitations of some font styles dictate that we use the line below.)

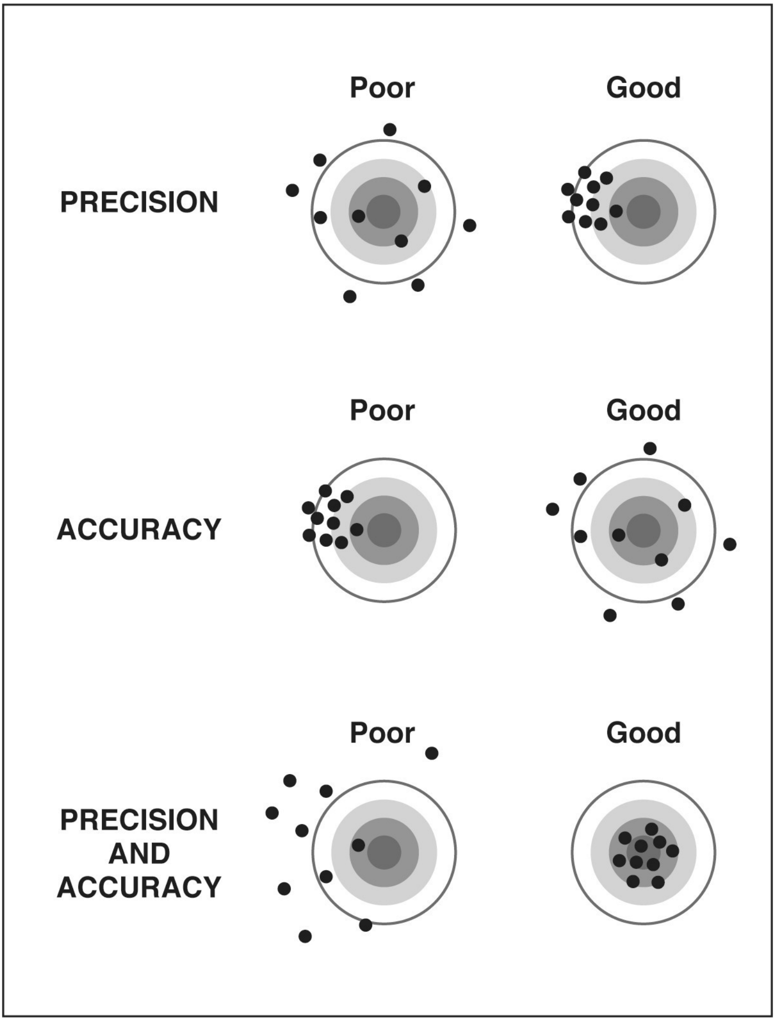

Figure 1. Illustration of precision and accuracy in target shooting.

For example, let's compare 23, a number that has two digits, with the number 250 that has three digits. Even though both numbers have two sig figs, 23 is a more precise number than 250 (without a bar over the zero or a decimal point at the end) while 23 and 25$\underline{0}$ have the same precision. For small bird count sizes, where you are counting individual birds, every digit will be a significant digit because you are counting by ones. What about a reported count of 20 birds? Does that mean that you counted 20 individual birds? Or did you count 19 or maybe 23, and then you rounded off to 20. Or maybe you estimated a single group as supporting 20 individuals without counting them.

When notated for precision, such as 20 or 20, the final zero has specific information for a scientist looking for information about precision.

When recording large numbers, care must be taken in writing the final count. If you counted 2,500 birds by counting in 100s, then you should indicate that by placing a bar under the 5 (2,500). This lets others know that you are certain it was 2 thousand and 5 hundred, but you counted in hundreds, so you are not as certain in the tens and ones. The 5 in this case is called the least significant figure. In the total count you measured to the nearest 1 part in 25, or 4%, which is not a bad measurement. What if you counted 2,650 by 50s? You can't underline the five (2650) because that indicates you measured to the nearest 10. The best way is to write it as 2,650 +/- 50. In this case you measured to the nearest 50 parts in 2,650 or around 2%, quite a good measurement. This is especially important in a number like 2,000. Written this way it suggests that you measured in thousands; 2,000 +/- 50 makes it much clearer that you measured to the nearest 50 and your measurement is much more precise than the number 2,000 by itself suggests.

Accuracy. Accuracy is how close your answer is to the correct number. In target shooting it is how close the average of all of your shots (not the individual shots) is to the center of the bullseye (Figure 1).

Accuracy Versus Precision: Accuracy may be affected by a bias or a systematic error. Precision means that the answer that you are getting is repeatable. Whether the result is close to the correct answer or not has nothing to do with precision (Figure 1).

Units of Measurement. Unit of measure refers to the type and size of the smallest individual whole item that could be counted. When measuring something, the device used will have units marked such as millimeters or inches, seconds, or years. In bird flocks it may be single birds, nesting pairs, or groups of 100. The smaller the unit of measurement, the more precision that is possible.

Level of Uncertainty. The level of uncertainty refers to the size of groups that are actually counted. The number of items in the level of uncertainty are multiples of the units of measurement. Level of uncertainty is often expressed as = +/- (x), where x is the quantity of the units being counted (e.g., 10s, 100s, 1000s of ducks). This multiple will determine the least significant figure and the level of uncertainty. This is related to the fineness of the measured units or the precision.

Every individual measurement is important in science, but because it is only one measurement, it has some associated uncertainty (often misleadingly called an error). Performing measurements many times (i.e., reproducibility), gives more certainty to the results by providing a measure of the uncertainty. Reproducibility with better instruments often can lead to new discoveries. For example, what appears with the naked eye to be a Ring-necked Duck (*Aythya collaris)*, when checked with a spotting scope, may in fact be a Tufted Duck (*A. fuligula)*. Even Newton's Laws of Physics needed revision with the advent of better equipment. The Newtonian Laws of classical mechanics were found to be inadequate when tested using results from high energy accelerators to measure the speed of particles travelling close to the speed of light. Scientists could have said that their instruments may have been badly calibrated, but it was obvious that their results were reproducible and outside the possible experimental uncertainties.

So, what does a single measurement represent? If the same experiment is repeated many times under the same conditions you would expect the values to fall around some mean value, sometimes higher, sometimes lower, but with a spread in values following a specific distribution. Obviously, acquiring more values with better precision confers a higher confidence in the mean value and reduces the zone of uncertainty. Great caution is warranted in accepting that a single value from a single count or experiment represents the mean value. Extremely rare events, in particular, require irrefutable evidence for acceptance. If you find a Dodo (*Raphus cucullatus*) you better be sure you have the evidence to support your claim.

Significant Figures as an Indication of Uncertainty. Significant figures are those digits in a number that are actually measured, including the last one or the right-most digit that can be read by interpolating between the finest units of measurement on the measuring device. That last measured digit to the right is called the least significant digit, which established the precision of the number and the level of uncertainty.

The decimal system is used in science because it simplifies calculations. The position of each digit represents a power of ten, also known as an order of magnitude. As you move to the left, each position is ten times the magnitude of the digit to its right. Measured numbers are written in a special way. Every measured digit in a number is a significant figure, also called a *sig fig*. How many sig figs does the number 200 have? It depends on whether or not you measured the last 2 zeros. Did you count by ones, tens, or hundreds? If you only counted by hundreds, then the number has 1 sig fig. If you counted by ones all the way to 200 then you have 3 sig figs, written as 200 or just 200. (with the decimal point). The final significant figure to the right, also called the least significant digit, defines both the level of precision and uncertainty in the number.

Scientific Notation. Very large numbers are usually written in scientific notation to avoid writing a lot of zeros. If you measured 25,200 birds counting in 100s you could write 25,200 to indicate your measurement has 3 significant (i.e., you measured digits to the nearest 100). An alternative is to write it in scientific notation as 2.52 x 10^4. This notation shows the 3 significant figures directly and avoids writing the insignificant unmeasured zeros at the end, which are called place holders. In scientific notation, the exponent is chosen so that there is only one significant figure to the left of the decimal and all other significant figures are to the right of the decimal.

Significant Figure Rule for Addition. The number with the least precision (greatest level of uncertainty) determines the precision of the final total when adding or subtracting. Sig figs have special rules for adding/subtracting. If you counted $2\underline{2}0$ birds at one site and 3 birds at another and want to find the total; 220 + 3 by normal arithmetic is 223, but you only counted in tens for the first number. The 3 in the second measurement will not change the total because the first number is already uncertain in the ones and 3 is closer to zero than to ten, so $2\underline{2}0$ + 3 = $2\underline{2}0$. The answer is $2\underline{2}0$, and not $22\underline{3}$ and the notation shows that you have rounded down from $2\underline{2}3$ to $2\underline{2}0$.

How should you express $2\underline{2}0$ + 8? Eight is closer to ten than zero so $2\underline{2}0$ + 8 = $2\underline{2}8$ = $2\underline{3}0$; you have rounded up 228 to $2\underline{3}0$. In other words, add or subtract and then round off (up or down) the final answer to the same level of precision as that of the number with the least precision. A 5 is usually rounded up, although some people like to alternate rounding a 5 between up and down to average out the rounding effect.

Significant Figure Rule for Multiplication. The number with the least number of sig figs determines the number of sig figs to keep in the product when multiplying. Sometimes you might want to multiply a measured number by an integer. For example, you counted 17 birds in migration across one site one day and you want to calculate how many birds would migrate in 31 days. 31 is an regarded as infinitely precise (i.e.,31.00000 ad infinitum). So, 31.0000 x 17 = 527. But 17 only has 2 sig figs whereas 527 has 3 sig figs. The number 17 means you measured to the nearest 1 in 17. You cannot say that just because you multiplied by 31 that you now have measured to the nearest 1 in 527. Instead, you round off to the least number of sig figs when multiplying, which in this case is 2 coming from the 17. So, 527 is rounded to $5\underline{3}0$.

It takes some practice to get comfortable working with sig figs. Almost every high school physics and chemistry class (and even many college classes) begin with how to write and work with measured numbers in order to get the most out of the measurement or calculation, but no more than is warranted. Don't claim results that are not warranted by your precision, but also don't throw away important information contained in your measurement.

Conclusion

Animal counts are an important source of information for a wide variety of purposes. In particular, many ongoing environmental threats may affect bird populations, including climate change, pesticide residue problems, habitat loss, and human disturbance. Birds may provide an advanced or early warning that can alert humans to the need for action to address these environmental changes. To better understand what is happening we need data that are reliable, which means quantitative data with estimates of the uncertainties. Better data, properly quantified, with better estimates, and with the significant figures properly indicating the levels of uncertainty in each quantity, will support better science and, we hope, better decisions.

Snow Geese (*Anser caerulescens*). 16 December 2017. Yolo Co., California.
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