How to weigh a donkey in the Kenyan countryside

Donkeys play a crucial role in the lives of rural Kenyans. When they fall sick, vets need a quick and accurate method of weighing the animals to administer the right dosage of drugs. The humble nomogram can help, as **Kate Milner** and **Jonathan Rougier** explain.

Picture yourself as a rural Kenyan farmer. Among your most valuable assets are your donkeys – hardy creatures that serve to transport crops, water and building materials. They also ferry people about, and are sometimes used for ploughing. Now imagine one of your donkeys falls sick. Drugs are needed, but the right amount depends on the weight of the animal, and assessing this is easier said than done out in the field.

However, if the vet has a tape measure to hand, then she can weigh the animal indirectly using a statistical tool called a nomogram, which can translate tape measurements into weights.


Kenyan donkeys, descended from the Nubian wild ass and the Somali wild ass. Photo: Kate Milner

In 2010, The Donkey Sanctuary, a UK registered charity based in Sidmouth, Devon, funded Kate Milner (co-author of this article) to travel to Kenya to assemble a data set and construct a parallel-scale nomogram for predicting the weight of Kenyan donkeys according to their other more accessible measurements.

The current population of donkeys in Kenya is estimated to be about 1.8 million. The predominant breeds are descendants and crosses of the Nubian wild ass (*Equus africanus africanus*) and the Somali wild ass (*Equus africanus somaliensis*).

Data for 544 donkeys were collected at 17 different sites in the regions surrounding Yatta district, in the Eastern province, and Naivasha district, in the Rift Valley province, during the period from 23 July to 11 August 2010. The predominant use of donkeys in the Yatta district is as pack donkeys, whereas in the Naivasha district they are mainly used to pull carts. The donkeys were brought to the sites for de-worming by The Donkey Sanctuary, and – where possible – all presented donkeys were included in the study, excluding those that were pregnant or had visible disease. Where that was too many to assess, a sample was used.

Four measurements were made for each donkey: liveweight (kg), heart girth (cm), height (cm), and length (cm). Heart girth is the circumference of the body, measured just behind the front legs. Height is to the highest point of the withers – the place where the donkey's neck connects to its back – taken by using a measuring stick. Length was from the point of the elbow to the tuber ischii or pin bone, which is the rearmost point of the pelvis. Donkeys were weighed on an electrical weighing platform – a piece of equipment not readily available to a vet in the field, and one that the nomogram would stand in for. Weights were recorded to the nearest kilogram. To check repeatability, 31 donkeys were weighed twice, with other donkeys being weighed between the two measurements. No weights varied by more than 1 kg.

In rural Kenya, donkeys transport crops, water and building materials. They also ferry people about, and are sometimes used for ploughing

Each donkey also had its age and sex recorded, and was assigned a body condition score (BCS) – a scale running from 1 (emaciated) through 3 (healthy) to 5 (obese), including half scores. Age was assessed from the donkey's teeth and divided into categories of “less than 2”, “2–5”, “5–10”, “10–15” “15–20” and “over 20” years. Sex was “stallion”, “gelding”, or “female” – a gelding being a castrated stallion.

Donkeys were de-wormed and marked with a crayon immediately after data collection to avoid them being recorded for a second time. Three of the 544 donkeys were excluded from the statistical analysis as being unrepresentative: one was a baby, one had a BCS of 1 – so was too emaciated – and one, with a BCS of 4.5, was very overweight.

Measure for measure

With our data set to hand, we were ready to start building our nomogram, which is, at its simplest, a diagram that can convert combinations of two values (lengths in our case) into a third (weight).

Nomograms have been used before to predict weight on the basis of simpler tape measurements, including for horses, mules and donkeys.[1–4] What we present here is a more statistical treatment, which we hope can serve as a template for other similar studies. We considered a richer set of possible models, an appropriate loss function for choosing between them, the constraints of practical usage, and a careful assessment of accuracy. All of our code and data, and a fuller mathematical treatment, can be found online at bit.ly/donkeysnomogram.

The mathematics of parallel-scale nomograms are explained in the box below, and our nomogram is shown in Figure 4. Their main advantage is ease of use in the field. A vet might make two measurements, and mark these as crosses on two of the axes. She might then join the crosses with a freehand straight line, or a ruled line if she has a straight edge handy – it would be sensible to ensure that the two outer axes are not more than a pencil-length apart. The nomograms could be made available as a pad of disposable sheets, or as a single reusable laminated sheet. A practical feature of nomograms is that they are invariant to changes in the aspect ratio. You can stretch them vertically or horizontally, which might happen when the nomogram is printed or photocopied, and they will still work.

There are more complicated nomograms than parallel-scale nomograms. Some of these are very beautiful, and the mathematics is intriguing.[5] But while these allow for richer relationships – possibly with more than three quantities – they are also harder to use, so we will stick with parallel-scale nomograms.

In mathematical terms, a donkey is basically an elliptical cylinder with appendages. Therefore, we expect its weight to be approximately proportional to Girth^2 × Length. It is possible that a donkey's less cylindrical aspects could be accommodated by also including height as an additional predictor; however, this cannot be represented in a parallel-scale nomogram. Therefore our starting point is the model equation:

$$\underbrace{a+b\cdot\log(\text{Girth})}_{f(\text{Girth})}+\underbrace{c\cdot\log(\text{Length})}_{g(\text{Length})}=h(\text{Weight})$$

But it is an empirical question whether we might do better replacing length with height. (NB. We used a mathematical technique called the Box–Cox power transformation to determine what form the function h should take. It uses a parameter lambda (λ). Again, full details are online at bit.ly/donkeysnomogram.)

We also have the possibility of adjustments for discrete factors, namely BCS, age and sex. Adjustments such as “add 5 kg for a gelding” are simple enough to be expressed in the rubric underneath the nomogram. Interactions, on the other hand, such as “subtract 5 kg for an animal

Building a nomogram

Suppose that three quantities x, y and z are related in the form:

$$f(x) + g(y) = h(z)$$

Here x and y could be the height and girth of the donkey, and z could be its weight. The functions f, g and h are monotonic (i.e. always increasing or always decreasing). It is possible to represent the relationship pictorially as a parallel-scale nomogram.

In a parallel-scale nomogram there is a vertical axis for each quantity, and a straight edge connecting values on any two axes intersects the correct value on the third. Figure 4 is an example of a parallel-scale nomogram. The geometrical construction of such a nomogram is shown in Figure 6.

The problem in constructing a nomogram is to find vertical scales for the three axes – α, β and γ in Figure 6 – and the position of the central axis along the baseline – a value for u. Mathematics combined with experimental data can determine which values of these four unknowns will give our nomogram the most accurate estimates for the weight of our donkey, based on its height and girth. Doerfler[5] provides an excellent review of nomograms, on which our explanations are based.

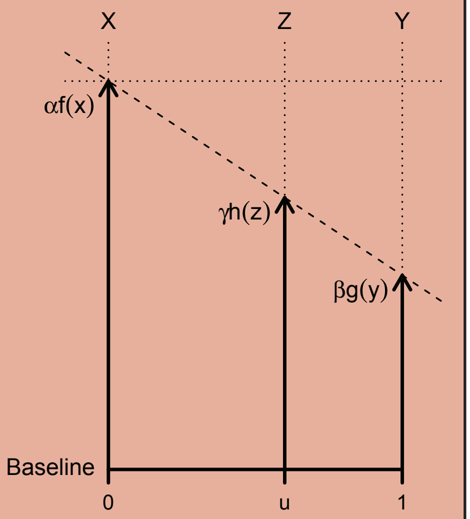

Figure 6. Geometry of a parallel-scale nomogram, after Figure 2 in Doerfler[5]

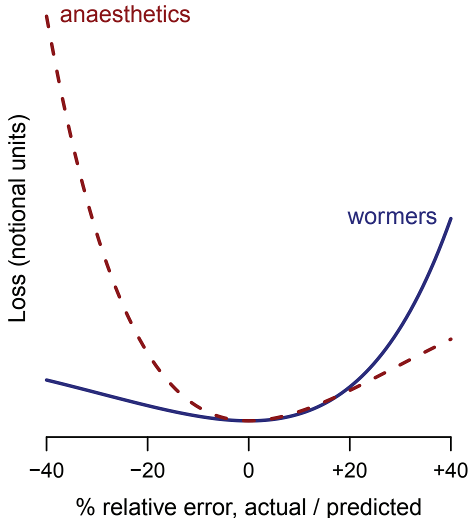

Figure 1. Two loss functions for predicting a donkey's weight. The blue line represents wormers and antibiotics, and the red dashed line represents anaesthetics and analgesics. Note that a negative relative error corresponds to an overdose

which is both a gelding and between 5 and 10 years old" are more prone to error in the field, so we avoided them.

For the same reason, we favour additive adjustments in units of kilograms, rather than proportionate adjustments in percentage units, even though the latter might be more plausible physiologically.

Model selection

We now have a set of possible models: we could use either length or height as the second predictor, and we have a range of values for the parameter lambda that determines the *h* function on the right-hand side of the equation. In addition, we have another range of values for the additive adjustments for sex and age. We fitted our models using least-squares regression. But which model do we prefer?

Consider the loss function, from the point of view of the donkey's health. This loss function is the cost of getting it wrong. It depends, among other things, on the drug that is being prescribed. For drugs such as wormers and antibiotics the therapeutic window is quite wide, and it is better to overdose the donkey because otherwise the infestation/infection might not be treated, and an underdose might lead to drug resistance. For drugs such as anaesthetics and analgesics the therapeutic window is narrower – the effect is more sensitive to the weight of the donkey – and it is better to underdose because the effect can be observed and if the donkey is still in pain or is not getting better you can always give it more. So we actually have two loss functions: ideally our preferred model would be the best model under both of them. Figure 1 shows the two loss functions we use; these are quadratic functions which we have scaled and tilted to reflect our concerns.

Note that we have defined the relative error in Figure 1 as "actual/predicted". This is because the value available to the vet is the donkey's predicted weight, not the actual weight, and the natural question for her to ask is "How different is this donkey's actual weight from its predicted weight of 175 kg?" (say). Thus a relative error of −10% indicates that the actual weight is 10% smaller than predicted, and hence the risk is of overdosing, not underdosing. Figure 1 shows that we consider a 40% overdose of anaesthetics to be much more serious than a 40% underdose of wormers.

For effective treatment it is crucial that we provide a reliable assessment of our tool's accuracy, uncontaminated by our data-driven modelling decisions. Therefore we set aside every fifth case in our data set after ordering by weight, to be used purely to assess accuracy.

Proceeding with the remaining four-fifths of our data set, Figure 2 shows the sample mean loss values for the length model versus the height model, for different values of their parameters and for the two different loss functions.

For both loss functions, length beats height, as we anticipated from our "cylinder with appendages" model. Looking at the length model, the optimal value for lambda seems to be $\lambda = 0.5$, which gives us the function *h* as:

$$h(\text{Weight}) = 2\left(\sqrt{\text{Weight}} - 1\right)$$

Now we turn to the additive adjustments. We are looking to remove factors, and recode the levels of those that remain, to make our tool as easy as possible to use in the field.

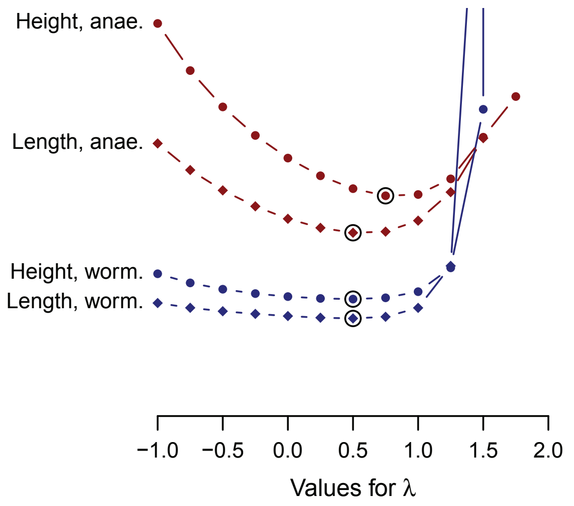

Figure 2. Sample mean loss values for the two loss functions in Figure 1, for length versus height as the second quantity, and for a range of values of the Box–Cox parameter λ. The minimum values are circled

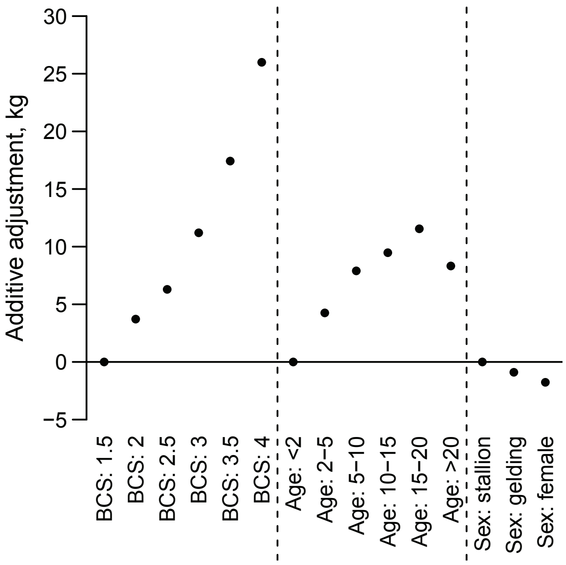

Figure 3. The estimated additive adjustments for the factors, with length as the second quantity, and λ = 0.5

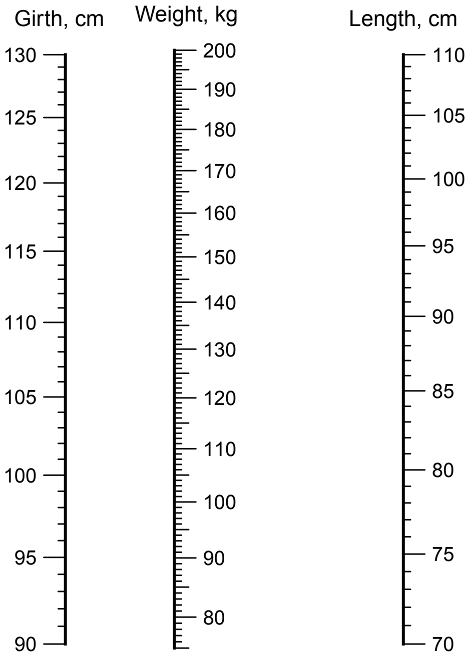

Figure 4. Nomogram for Kenyan donkeys with BCS = 3 and age ≥ 5. To predict weight, join the girth and length values with a straight line

The estimated factors are shown in Figure 3. Clearly sex can be removed, as the weight adjustments for stallion, female or gelding are too small to worry about; but age and BCS are both important.

We recoded age from our original six categories into three levels, "less than 2 years", "2–5 years" and "over 5 years", which is physiologically plausible – and far easier for a vet to determine, either from the animal itself or from the owner's knowledge. The clearly differentiated values for BCS suggest that the qualitative scale is well defined. Possibly we could merge BCS levels 2 and 2.5, as their adjustments are similar, but the saving would be minimal.

We refitted the model with these recoded factors, taking the most populous levels of body condition and age as the reference (BCS = 3 and age ≥ 5). Our resulting model is:

$$f(\text{Girth}) = -107.0 + 19.91 \cdot \log(\text{Girth})$$

$$g(\text{Length}) = 7.712 \cdot \log(\text{Length})$$

and, as mentioned above,

$$h(\text{Weight}) = 2\left(\sqrt{\text{Weight}} - 1\right)$$

The resulting nomogram is shown in Figure 4. Readers can confirm themselves that a donkey of more than 5 years of age, with a BCS of 3, a girth of 122 cm and a length of 103 cm, weighs approximately 175 kg. This corresponds to donkey number 78 in our data set, whose actual weight is 183 kg. The relative error is about +5%. The additive adjustments for those donkeys of different ages and body conditions are given in Table 1, rounded to the nearest kilogram.

Table 1. Additive adjustments for factors at non-reference levels, in kilograms

Factor			
BCS		Age	
1.5	−10	<2	−8
2	−6	2–5	−4
2.5	−5	>5	none
3	none		
3.5	+6		
4	+14		

Finally, we assessed our tool's accuracy, using the hold-out sample of one-fifth of the donkeys that we mentioned previously. The prediction of weight proceeds exactly as if we were in the field; that is, we used only the information in Figure 4 and Table 1 to obtain our predictions, which we could then compare to the donkeys' actual weights. Figure 5 and Table 2 show that it is reasonable to claim that the typical accuracy of our tool is about ±10%, and that this is relatively consistent over the range of predicted weights from 75 to 200 kg.

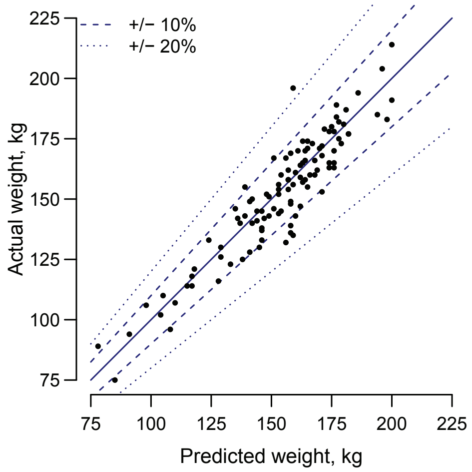

Figure 5. Hold-out sample of 108 donkeys. Predicted weight versus actual weight, with relative error bands

Table 2. Distribution of relative errors of our tool in the holdout sample of 108 donkeys

	Relative error, actual/predicted				
	< −10%	−10% to 0%	0% to +10%	+10% to +20%	> +20%
Proportion	8%	44%	44%	3%	1%

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