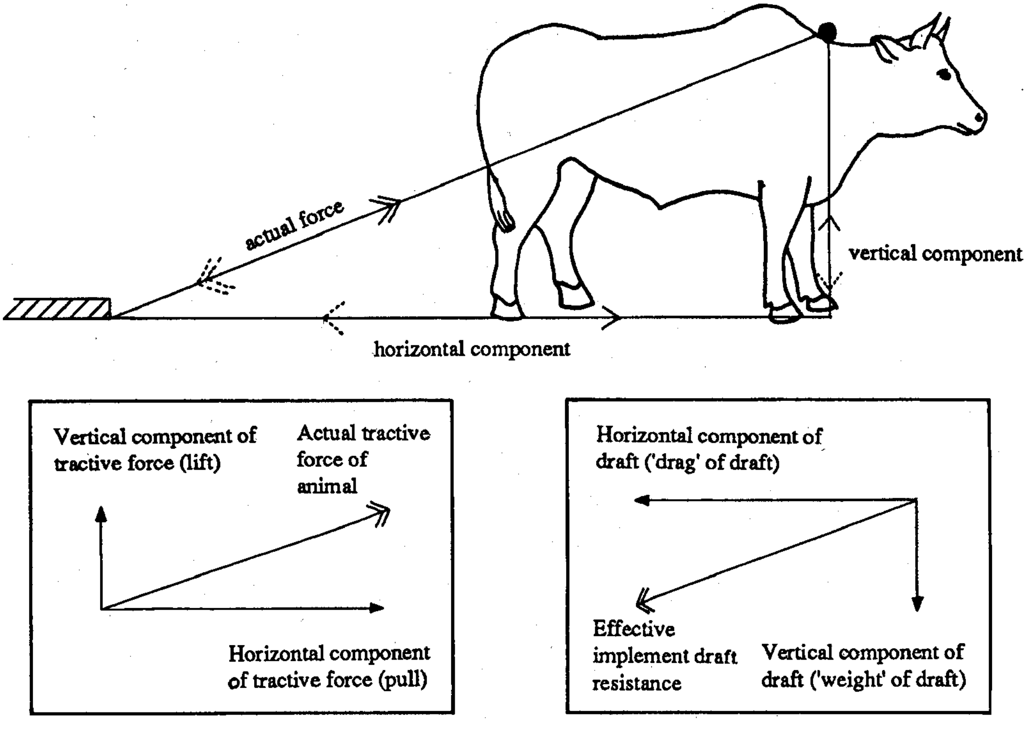
2. Some mechanical principles

2.1 A very simplified approach to some mechanical principles

Many agriculturalists seem to regard mathematics and physics with trepidation and tend to skip over presentations that remind them of their previous struggles with these subjects. It is therefore not intended to present any detailed analyses of the dynamics of animal traction equipment, with impressive combinations of arrows, cosines, integration signs and Greek letters. For such technical details readers are referred to Devnani (1981), Viebig (1982), Crossley and Kilgour (1983), Goe (1987) and Matthews (1987). Nevertheless there are a few basic principles, which may be combined with common sense to provide a useful approach to animal traction equipment for people who would not consider grappling with the more complex theories of mechanics. Thus this brief section is intended to remind people of basic principles already known to them, and give some examples of the type of context in which they can be applied. In many cases, even a vague recollection of mathematical concepts learnt long ago, can help in interpreting and understanding different features of harnesses and equipment. Simple principles (rather than learned rules) can also be useful when it comes to assessing the advantages and disadvantages of various designs, and the significance of any modifications and adjustments.

In addition to some basic mechanical principles, it will be helpful to be familiar with the main units of measurement relating to animal-powered implements. The day-to-day application of such units is not essential because comparative performances are more relevant than absolute values in the majority of field situations: farmers are more concerned with whether a particular combination of animals and implement can achieve acceptable work in a reasonable time, than with numbers illustrating weights, draft and power. Nevertheless there are great advantages in using standard units of measurement since this facilitates exchange of information between people in different countries; in the past meaningful exchange has been hampered by the wide range of different units that have been used when assessing animal drawn implements (horsepower, kilowatts, kilogram force, pound force, newtons, joules, miles per hour, kilometres per hour, metres per second, square metres per hour, hours per hectare, acres per day, etc.). Whenever practicable, internationally accepted standard units have been used in this book. Such units are merely convenient measures of magnitude, and do not convey any information as to the authority or reliability of numbers. While measurements obtained under accepted standard and repeatable test conditions can be widely applicable, there are very few standard measurements relating to animal draft, other than implement and animal weight and physical dimensions. When draft animals work pulling implements in a farmer's field or at a research station there are so many highly specific variables influencing the situation that the actual figures may have little relevance away from the conditions in which they were obtained. Thus although the use of international *units* is to be encouraged, these should not be confused with international test standards, and great care should be taken when interpreting data



Tractive forces

Resistance forces

Fig. 2-1: Illustration of the vertical and horizontal components of draft forces.

obtained in different circumstances. Similarly, because local conditions are so variable, it is generally unwise to ascribe "typical" values to agricultural operations. Nevertheless in order to make readers more familiar with the units that will be used in subsequent chapters, a few illustrative values of force, work and power will be given, merely as examples.

2.2 Forces and vectors

The first mechanical principles that might be recalled are those relating to forces. (Some people may even remember that Newton's first law was that a body will remain at rest or in straight-line motion unless acted upon by a force. His second related to changes in momentum and direction of movement as a result of forces, while his third was that actions and reactions are equal in magnitude and opposite in direction).

The standard unit of force is a newton (symbol N). The definition of a newton is based on the force resulting from acceleration acting on a mass of one kilogram. Since the acceleration due to the Earth's gravity is about 9.8 metres per sec^2, the weight of one kilogram mass (on most of the earth's surface) is about 9.8 newtons, i.e. *one kilogram of mass weighs about 10 newtons*. Thus although some purists may object, for all practical purposes a newton can be simply considered as a unit of force equivalent to 100 grams weight. Thus 10 N is equivalent to one kilogram (1 kg or 2.2 lb). Newton units are used in this book as these are the accepted international standard, and will be found in other references. Older texts have generally referred to kilograms force (1 kg f ≈10 N) or pounds force (1 lb f ≈ 4.5 N). Some authors have used decanewtons (dN) which are broadly equivalent to kilograms and some have used kilonewtons (kN) equivalent to 100kg force. However for most people it should be sufficient to remember that *dividing the newton figure by 10* will give the kilogram equivalent. By way of illustration, a low-draft implement such as a light seeder might impose a draft resistance force of about 200N; a small mouldboard plow in light soils might require a tractive force of 500N while a double mouldboard plow in heavy soils might require a force of 2000N.

In scientific terms "weight" is actually a force, since it depends on the acceleration of gravity. A body can appear "weightless" in space, even though its "mass" does not change. The standard units of mass are grams and kilograms, while it has been noted that the units of force are newtons. A spring balance, even one calibrated in kilograms, actually measures weight not mass, and will give slightly different readings at different altitudes. Purists would calibrate spring balances in newtons, whether they are to be used as weighing instruments or as dynamometers for measuring draft forces. However for those concerned mainly with tilling the earth's surface, gravity can be considered approximately constant, and the interchange of the words "mass" and "weight" is unlikely to be a source of confusion. For this reason, the word "weight" will often be used in this book in the loose, colloquial sense, in which weight is measured in kilograms, rather than newtons.

Forces have direction as well as magnitude, and the concept of vectors is useful in studying them. Forces can be analysed in terms of three axes at right angles to each other, although many can be considered more simply and conveniently as acting in just one plane. In such cases a "diagonal" force (such as the pull on a traction chain), can be thought of in terms of vertical and horizontal components (Fig. 2-1). Such a pull has an upward component and a forward component. If the pull were at an angle of 45°, these horizontal and vertical forces would be equal, so that as much of the applied force is being used in "lifting" as in "pulling". If it were possible to change the 45° pull into one that was almost parallel to the ground, the same force would have a much greater horizontal (forward) effect. One means of achieving a more effective horizontal force would be the use of a very long traction chain, and another would be to lower the point from which it were pulled. In terms of horizontal pull, short-legged oxen with a low-hitched harness and a very long traction chain would be more efficient than long-legged camels with a high hump harness and short chain. This exaggerated example illustrates two points: firstly that agriculturalists do not have to be engineers to be able to consider in a very simple but useful way the forces involved in the application of harnesses and equipment, and that such consideration may well lead to ideas for improving field adjustments or overall designs; secondly what may be theoretically optimal in terms of one aspect of efficiency may not be appropriate in terms of operational convenience or animal availability. Over-long chains make turning very difficult and short legged mini-beasts may not have sufficient power, speed or endurance. In practice, design considerations such as convenience, cost, availability and even appearance may outweigh technical refinements.

Fig. 2-2 gives a highly simplified diagram of some major forces acting on a plow. Some readers may have seen comparable diagrams with arrows going in other directions. This can be explained with reference to Newton's third law, since all the forces cited will have opposing forces (the pull of the animals is opposed by the draft of the implement; the downward force of the yoke due to gravity and the vertical component of the draft is opposed by the body of the animal as it stands and pulls). Fig. 2-2 is not actually a vector diagram, as it merely shows the directions of the

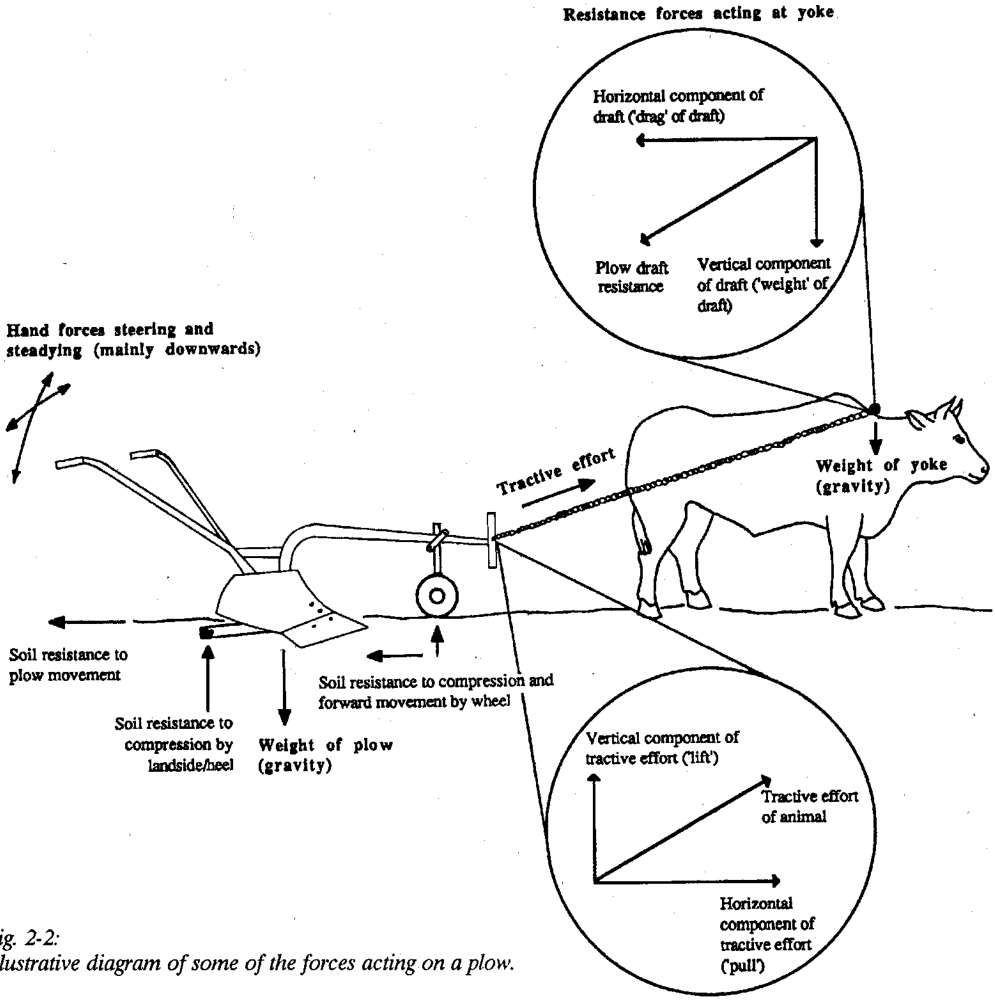


Fig. 2-2:
Illustrative diagram of some of the forces acting on a plow.

various forces, not their values. In a mathematical vector diagram, or triangle of forces, the lengths of the sides are directly proportional to the forces. In practice vectors are seldom included in diagrams of harnesses and plows since the actual forces are highly variable. If a comprehensive picture of all the different forces (actions and reactions) at work during a field operation were to be included in a diagram, a veritable spider's web of arrows could be created before even venturing into the third dimension. Fortunately for many practical purposes the different forces can be considered quite separately, and this simplified approach can be particularly useful when reviewing settings and adjustments.

Although emphasis in this discussion has been placed on the forces associated with plows, similar forces are involved with other animal-drawn implements. For tillage implements, the soil resistance to forward movement is generally the most crucial. For wheeled implements or animal-powered gears, internal frictional resistance to the rotation of wheels, bearings or gears may be at least as important as the draft forces between the implement and the environment.

Summary of the units cited in this book and some equivalents

Quantity	**Units**	**Symbol**	**Comparisons and approximate conversions**
Mass	kilogram gram tonne	kg g t	1 kg = 2.2 lb; 1 lb = 0.45 kg 1000 g = 1 kg 1 t = 1000kg ≈ 1 imp ton
Length	kilometre metre centimetre millimetre	km m cm mm	1 km = 0.621 miles; 1 mile = 1.61 km 1 m = 100 cm = 1000 mm = 1.09 yard = 3.28 ft 1 cm = 0.394 inch; 1 inch = 2.54 cm 1 mm = 0.04 inch
Time	second, hour, day	s, h, d	1 h = 60 mins = 3600 s
Area	square metre hectare	m^2 ha	1 m^2 =1.20 sq yd; 1 sq yd = 0.84 m^2 1 ha = 10,000 m^2 = 2.47acre; 1 acre = 0.405 ha
Volume	cubic metre litre	m^3 l	1 m^3 = 1000 litres = 220 gallons = 35.3 cu. ft 1 l = 0.22 imp gallons
Speed	metres per second kilometres per hour	m/s, m s^{-1} km/h or km h^{-1}	1 m/s =1 m s^{-1} = 3.6 kmh^{-1} = 2.24 mph = 3.28 ft s^{-1} 1 km/h = 1 km h^{-1} = 0.278 m s^{-1} = 0.62 mph; 1 mph = 1.6 km h^{-1}
Force	newton decanewton kilonewton	N dN kN	1 N = 9.8 (≈10) kg force (kgf) = 0.225 lb force (lbf) 1 dN =10 N = 1 kgf = 2.25 lbf 1 kN = 1000 N =100 kgf =225 lbf =0.10 tonf
Work or energy	joule kilojoule megajoule	J kJ MJ	1 J = 1 newton metre (Nm) 1 kJ = 1000 J =737 ft.lb 1 MJ = 1000 kJ = 1,000,000 J
Power	watt kilowatt	W kW	1 W = 1 joule per second = 1 Nm s^{-1} 1 kW = 1000 W = 1.34 hp = 1.32 cv; 1 hp =0.75 kw

2.3 Work and power

Work involves moving a force through a distance. As an implement is pulled through the soil, the animal or team exerts a tractive force and as it moves across a field, it performs work. Work done is not a function of time, so that however long an operation takes, the actual work done is the same. Plowing a field to a particular standard and depth entails the same amount of work (in principle) whether it is completed in one morning, in one day or in many days, whether the work is done by a single animal, a pair, or by a large team, and whether the animals pull a narrow plow through a long distance or a wide plow through a shorter distance. (In practice there may be some small differences since some frictional forces vary with speed and surface to volume ratio). Although the actual work achieved in terms of plowing will be the same in all the cases cited, the number of animals and the *rate* of work may well have significant implications for total energy expenditure. (Animals are constantly using *metabolic* energy for maintenance, in a way comparable to the non-stop idling of a vehicle engine, so that a slow job or one involving more than one animal may involve higher metabolic energy expenditure; animals also perform work moving themselves, so that the shorter the distance they travel, the less work they do moving themselves; in such cases pulling a wide

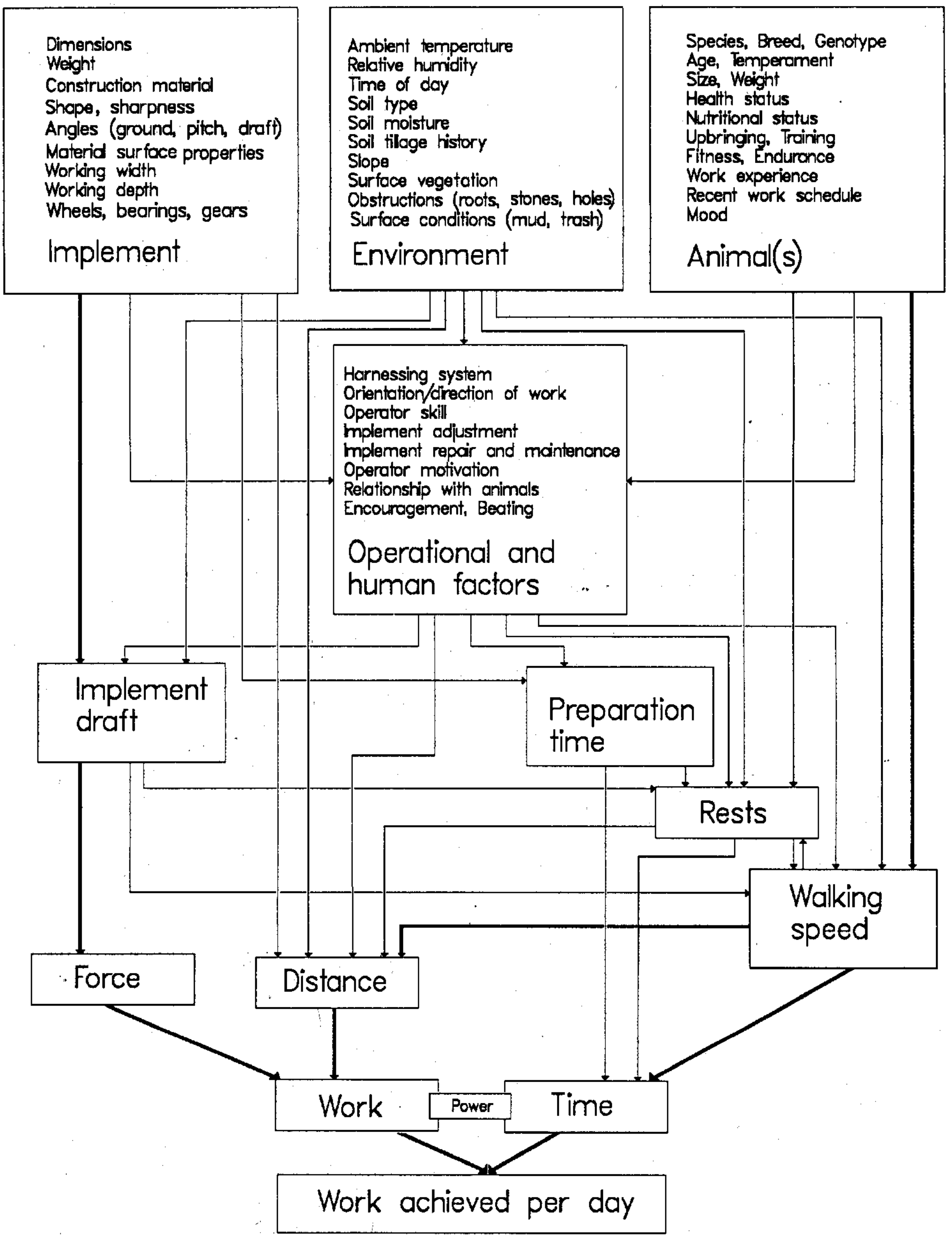


Fig. 2-3: Some of the factors influencing the work acheived per day by draft animals.
On the left side of the diagram: *the shape, weight, width and working depth of the implement largely determine its draft in the prevailing environment, and thus the force the animal(s) have to apply to pull the implement.*
On the right side of the diagram: *the breed, size, weight, training, fitness, temperament and work schedule of the animal(s), together with the implement draft, will largely determine the walking speed and thus the power output and, depending on the distance covered in the day, the resulting work achievement.*
Centre: *implement draft, walking speed and non-working time are greatly influenced by a wide variety of interacting environmental,operational and human factors, only some of which are shown here.*

implement though a short distance will involve less energy for walking than pulling a narrow implement through a long distance).

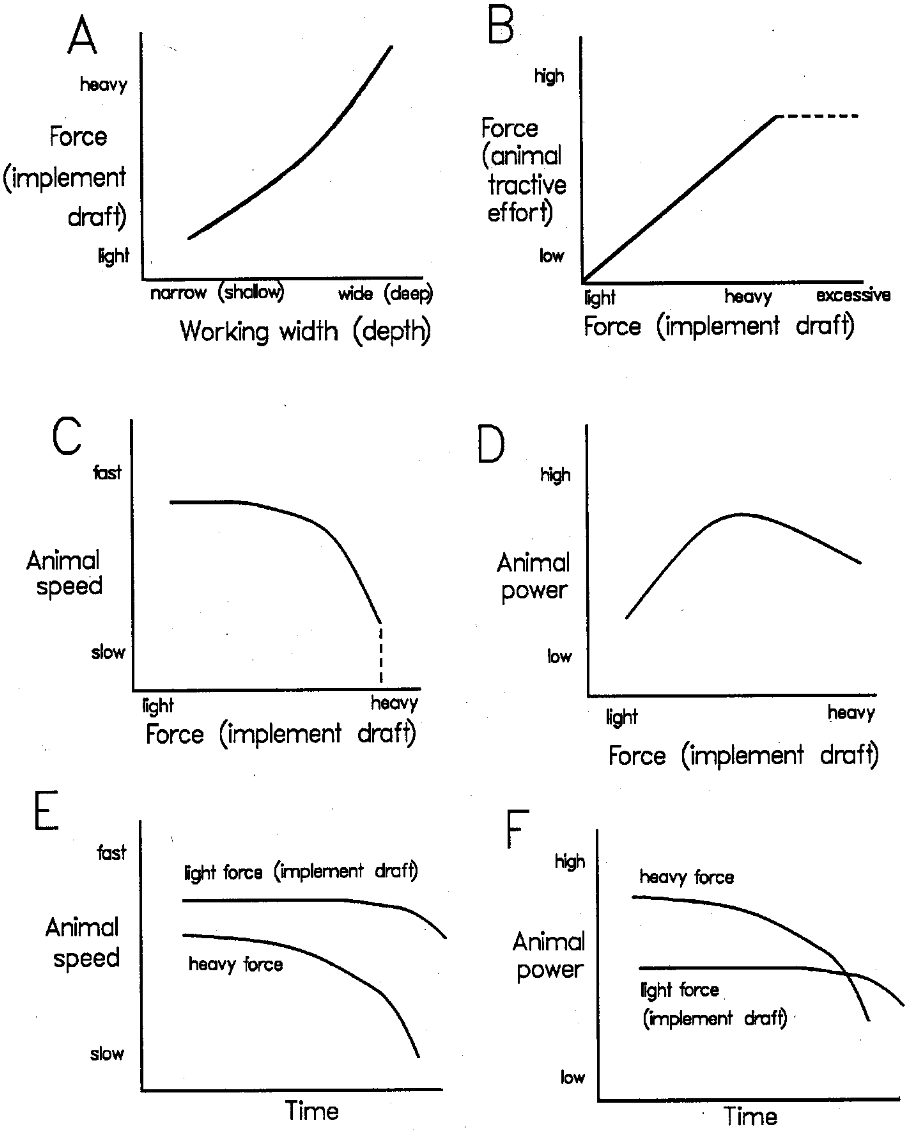
The units used to measure work are joules (J), kilojoules (kJ) or megajoules (MJ). A joule is the work of moving one newton through one metre. Since 1 kg weighs about 10 newtons, lifting one kilogram through one metre is equivalent to about 10 joules of work. Similarly pulling a 1000 N force through 1000 m (1 km) is equivalent to about one megajoule of work. By way of illustration, during a relatively light work schedule, a pair of 250 kg oxen might achieve 2.5 MJ of work in a day by pulling a 500 N force through a distance of 5000 m; in a more rigorous schedule, a pair of 350 kg oxen might achieve 12 MJ of work in a day by pulling a 800 N force through a distance of 15,000 m. Seeding a hectare of land with a low-draft (200 N) implement at 60 cm spacing (requiring travelling 17,000 m) might represent 3.3 MJ of work. Similarly plowing a hectare of land with a small 15cm mouldboard plow in light soils might involve work of 33 MJ (a 500 N force through 66,000 m, the distance a 15 cm implement has to travel to cover a hectare). In theory, plowing with a double mouldboard plow adjusted to the same depth would involve the same amount of work as the draft force would be doubled (2 x 500 N) but the distance moved would be halved (33,000 m). Plowing a hectare of similar soil slightly deeper with 25cm single (or double plow) might involve 40 J (a 1000 N force through 40,000 m or a 2000N force through 20,000 m).

Power is the *rate* of doing work, and therefore unlike work, power is a function of time. Historically power was assessed in terms of what a draft animal might perform, and was measured in units called *horsepower* (hp), units that are still quoted today in some countries. The "imperial" horsepower unit was suggested by James Watt who timed a horse and also his new steam engine as they pulled weights up a well shaft: he concluded that a horse could work at a rate equivalent to lifting a 550 pound weight through one foot in one second. A metric *horsepower*, or *cv* in French, was very slightly less, being the equivalent to lifting 75 kg through one metre in one second (1 cv = 0.986 hp). (In passing it may be noted that despite the implications of the word "horsepower", horses in Africa seldom perform sustained work at a rate of more than about 0.6 hp, although during bursts of rapid work they may produce very high power peaks of 6-7 hp).

Horsepower units have been replaced by the international standard unit of power, the watt and its multiple, the kilowatt. A watt is a unit of power is equivalent to one joule of work per second. Lifting one newton by one metre in one second requires a power of 1 watt (W). Similarly lifting one kilogram (i.e. 10 N) one metre (i.e. 10 joules of work) in one second requires a power of 10 watts. A kilowatt (kW) is 1000 W and 1 kW = 1.34 hp = 1.32 cv. For illustrative purposes, a pair of oxen walking quickly at one metre per second (1 m/s or 1 m s^{-1}) and pulling a load of 1000N, produce a *joint* work output of 1000 W or 1 kW. A single donkey pulling a 200 N draft seeder at a rate of 1 m s^{-1} works at the rate of 200 W.

For any particular force or amount of work, it is *speed* that determines power output. Pulling an implement that has a draft of 800 N at a speed of 0.8 m s^{-1} requires a power of 640 W, while to pull the same implement at 0.3 m s^{-1} requires only 240 W. Animals therefore tend to adjust their speed in reaction to the draft load and the reduction in speed is particularly noticeable with cattle.

It should be noted that while many of the terms such as force, draft, work and power have specific scientific definitions, they are also used in a more general and loose sense by agriculturalists and farmers. Subjectivity and context can bring to these words a wide variety of meanings. For example, oxen are often said to be more "powerful" than horses.



Important note: *these graphs are included only for the purpose of illustrating some general points, as described in the captions and discussed in the text. Their exact shape is* **not** *significant. These graphs should* **not** *be interpreted as demonstrating exact relationships between the variables involved.*

Fig. 2-4a: Some highly simplified, illustrative relationships between force, speed, power and time.
A: The draft of an implement increases with working width or working depth.
B: As implement draft (resistance force) increases, an animal has to exert an equal force in order to pull the implement at a steady speed. When the resistance is greater than the maximum pull of the animal, the animal may exert a force by straining at the implement, but it will not be able to move it.
C: As the draft of an implement increases beyond a certain point, an animal slows down and eventually stops.
D: As the draft of an implement increases, an animal increases its power output (power = force × speed), until a point when the increase in the force it exerts is more than offset by its decline in speed.
E: An animal with a light load maintains its normal walking speed for some time, although speed may eventually decline. An animal pulling a heavy load starts at a slower speed, and noticeably slows with time.
F: With a light load an animal maintains its (low) power output for some time, but with a heavy load its (higher) power falls off rapidly when it tires and slows. The cross-over of the graphs illustrates that the power output of an animal may be greater when a light load is pulled fast, than when a heavy load is pulled slowly.

Important note: *these graphs are included only for the purpose of illustrating some general points, as described in the captions and discussed in the text. Their exact shape is* **not** *significant. These graphs should* **not** *be interpreted as demonstrating exact relationships between the variables involved.*

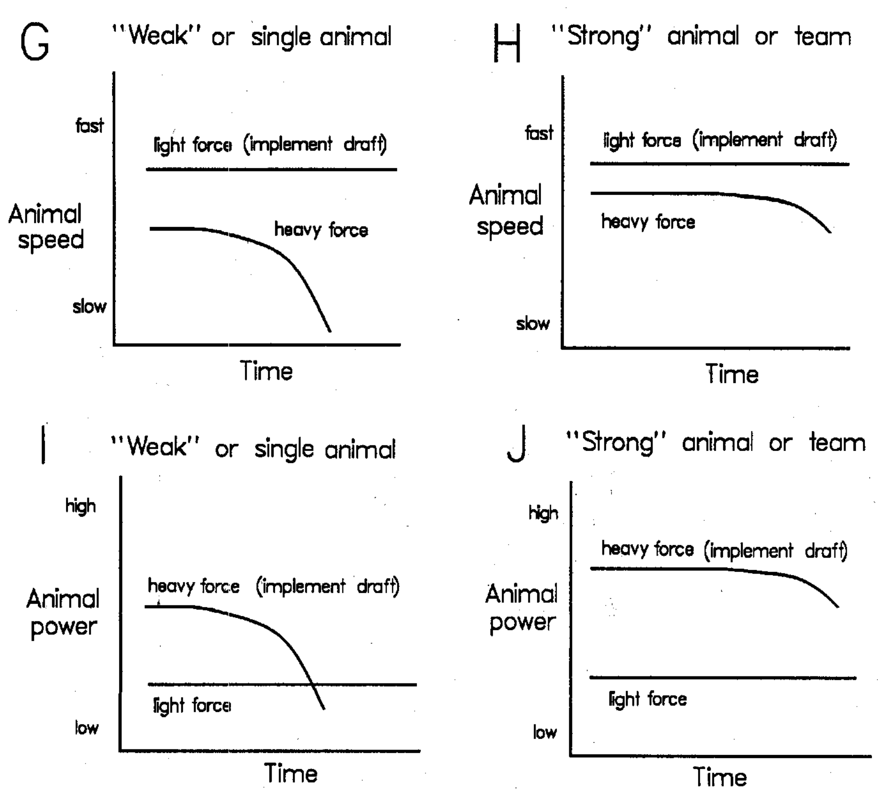


Fig. 2-4b: Some highly simplified, illustrative relationships between force, speed, power and time, showing some differences between "weak" and "strong" animals, or between single animals and teams.

G: With a light draft force (low-draft implement), the "weak" or single animal is able to walk fast and maintain its walking speed, but with the heavier load it starts at a slower speed and soon slows down significantly.

H: With a light load, the "strong" animal or team consistently walks at a fast speed (but no faster than the "weak" or single animal). With the heavier load the animal or team starts off at a slightly slower speed than when pulling only a light load, and maintains the speed well although it does declines after some time. The "stronger" animal or team invariably walks faster than the "weaker" or single when pulling the heavy draft.

I: The "weak" or single animal maintains its low power output with a light load, and since walking speed and implement draft are the same as those of the "strong" animal or team, its power output is equal to that of the "strong" animal or team (graph J). With the heavier load the animal initially provides power at a much greater level than with the light draft, but this rapidly falls off as the animal tires and slows down.

J: Although the animal or team is "strong", it cannot apply any more power than the "weak" animal or single when it pulls the same light-draft implement at the same speed (graph I). However with the heavier draft, the "strong" animal or team can maintain a high power output, which only drops off as the animal(s) tire and slow.

Sources consulted in compiling these illustrative graphs included: Vaugh, 1945; Hussain et al, 1980; Ayre, 1981; Varshney et al, 1982; Crossley and Kilgour, 1983; Lawrence and Pearson, 1985; Kebede and Pathak, 1987; Betker and Klaij, 1988; Bansal et al, 1989; Lawrence, 1989; Pearson et al, 1989.

What is usually meant by this is that oxen may be better at sustaining a heavy draft force for a longer period than a horse. However because of their higher speed, horses can generally develop more actual "power" than oxen.

In any given situation, a very large number of different, interacting parameters relating to the animal(s), the implement, the harnessing, the environment and the human operators will determine the amount of work that can be achieved. Some of these are illustrated in Fig. 2-3 and further discussed in Chapter 10. However it may be helpful to remember the following highly simplified summary. It is the implement (its size, weight, width, depth, etc.) and the environment (soil conditions, obstructions, etc.) that together determine the draft force. These can be effected by the operator (settings for depth and width of work, working condition of implement, etc.). Since the draft is determined by the implement and the environment, this will be broadly the same whether it is pulled by one animal or many animals, and whether it is pulled quickly or slowly. What is determined by the animal(s), is the speed at which the implement is moved. The achieved speed (and therefore the power output) will depend on the draft of the implement, the power and condition of the animals, environmental conditions and the behaviour of the operator. In response to high draft forces or fatigue, animals slow their walking pace and take more rests, so reducing the work they do in a given time. Some of these relationships are illustrated in a simplified way in Fig. 2-4.

Harnesses link animals to implements; while they do not alter the actual draft of the implement, they can influence how the draft is partitioned between vertical and horizontal vectors. Harnesses do vary slightly in their efficiency as transmission systems, so that greater or lesser amounts of energy are dissipated in the harnessing system itself or in unproductive work. Harnesses do *not* affect the intrinsic power of an animal, which is determined largely by its species, size, weight and past history. However through ergonomic aspects of design, notably those relating to comfort, harnesses may influence an animal's ability and/or willingness to *use* its power. This is discussed further in Chapter 5.

2.4 Levers

Much to do with equipment design and adjustment can be explained by reference to principles of levers. The "eveners" used in the harnessing of multiple teams are simple levers, as are yokes. In either case if the position of attachment of the hitching is moved from a central position, levers of unequal length are created. The weaker animal requires a longer lever to help it, while the stronger can make do with the shorter one. Pressing down on the handle(s) of a plow can be thought of as a lever action. The rear of the plow-body acts as a fulcrum (pivoting

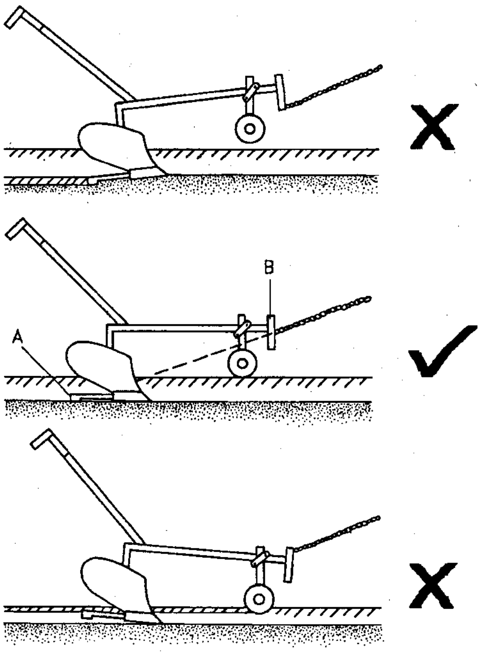


Fig. 2-5: Pitch adjustment of a plow (exaggerated).
A. Heel or end of the landside.
B. Hake or vertical regulator.
***Top:** Incorrect adjustment: wheel lifts off the ground and heel digs in too deeply. (Problem: too much leverage low down on regulator; solution raise the chain attachment. A similar problem is caused if the chain is too short).*
***Middle:** Correct adjustment.*
***Bottom:** Incorrect adjustment: wheel digs into soil and heel lifts out of furrow. (Problem: too much leverage high on regulator; solution lower the chain attachment. A similar problem is caused if the chain is too long).*

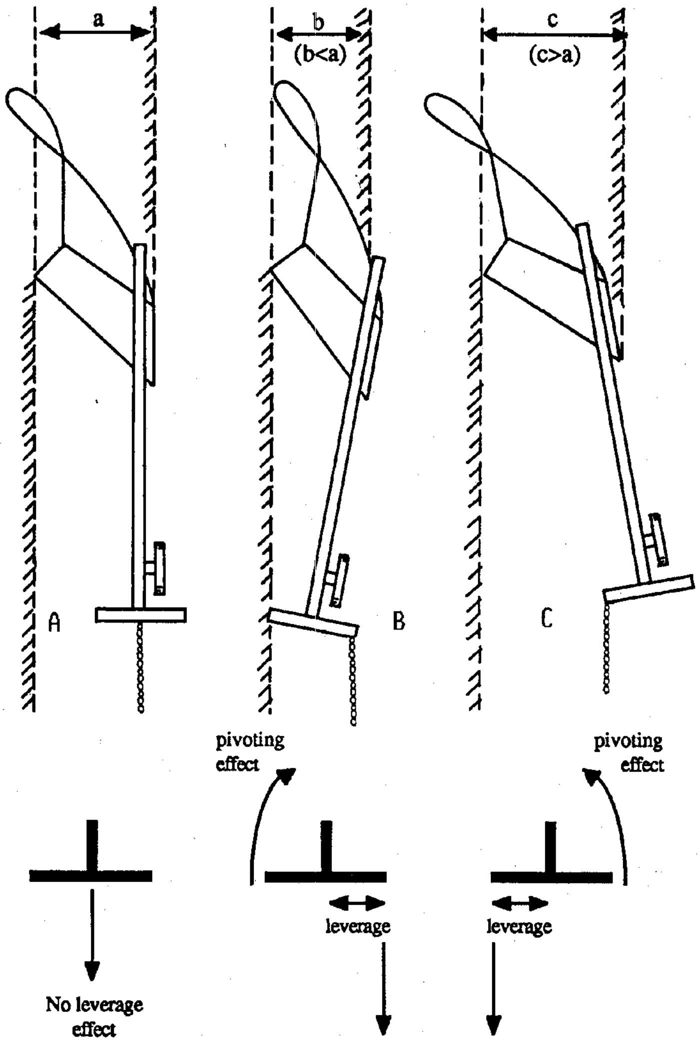


Fig. 2-6: Horizontal adjustment of a plow (exaggerated).

A). Chain attached to central position. Plow cuts furrow equal in width to share size.

B). Chain attached towards unplowed land. Lever effect of the regulator causes slight pivoting around central position which causes share to cut a narrower furrow.

C). Chain attached towards furrow. Lever effect of the regulator causes slight pivoting around central position which makes the plow body move through the soil slightly "crabwise" so that the share cuts a wider furrow.

Source: after Starkey, 1981

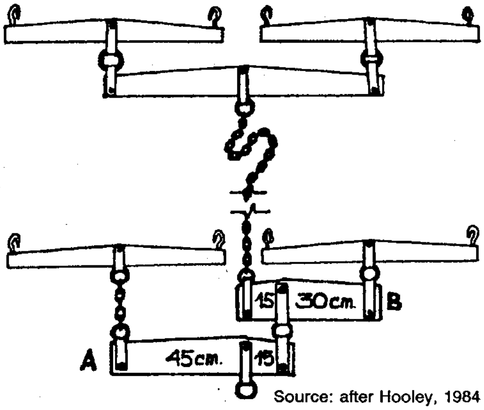
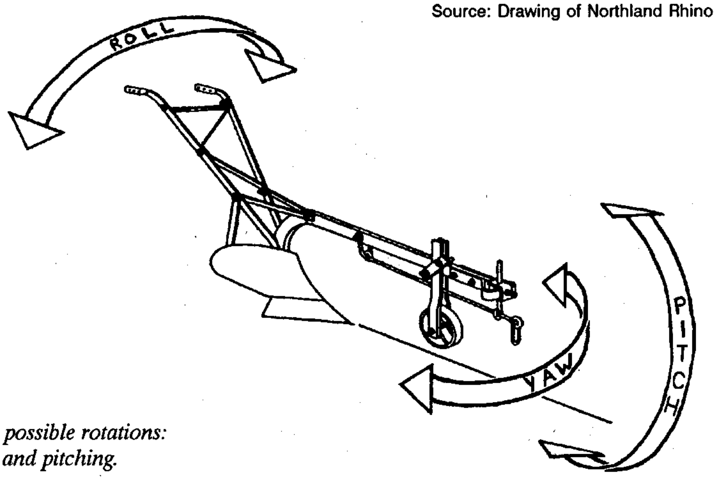


Fig. 2-7 (right): Eveners for a four-horse team.

The front (top) evener is symmetrical as the two front animals are assumed to be of equal strength. Evener B has a short lever of 15 cm to take the force of the front two animals, and a longer lever (2 x 15 = 30 cm) to allow rear right-hand animal to match this. Evener A provides a short lever for the three animals attached to it and a long lever (3 x 15 = 45 cm) to allow the rear left-hand animal to provide eqivalent and balancing leverage.

Source: after Hooley, 1984



Source: Drawing of Northland Rhino plow after ILO, 1983g

Fig. 2-8: Three possible rotations: rolling, yawing and pitching.

point) so that downward leverage on the handle(s) causes the share to move upwards to a shallower depth. (Such a movement is one of the many reflex responses associated with plowing; it is most obvious when plowing at a reasonable speed in light soils; in heavier soils and at low speeds the plow is unlikely to be sufficiently in equilibrium to allow the operator to distinguish between the different leverage effects).

The width and pitch adjustments of a plow can also be understood in terms of levers. Moving the chain attachment or adjustment from a central position will cause a slight leverage effect, pivoting around that central attachment point. Moving the chain in either horizontal direction will cause the plow beam to pivot round a little, and the plow body will move through the soil slightly crabwise, as shown (exaggerated) in Fig. 2-6. If the movement is towards the unplowed land, the share will be skewed so that it is even more angled to the direction of movement, and thus it will cut a smaller slice of soil. If the traction chain movement is in the direction of the plowed land, the share will be pulled round so that it cuts a wider furrow. The pitch adjustment on the hake can be viewed in a similar way, as shown in exaggerated form in Fig. 2-5. Moving the chain upward causes the plow to pivot so that the heel rises and the share points downwards. Moving the chain down causes the heel to press down and the share to point upwards.

Finally, in practical situations it is rare for all the forces acting on a body to be even and constant, so that any object in motion (be it a boat, aeroplane or plow) has a tendency to move in orientation in one or more planes. For convenience these are described in terms of three major planes at right angles to each other. The complex movements of an implement in use can be systematically analysed with reference to these three planes, and instability can be described in terms of pitching, rolling and yawing as illustrated in Fig. 2-8.

A simple swing plow is relatively unstable and thus requires considerable human effort to counteract all the tendencies to move out of equilibrium. *Pitching* (that is when the front moves up or down relative to the back, consequently changing working depth) can be minimized by using a land wheel (or skid) and a long landside with heel. *Rolling* (tipping over sideways) can be reduced with the use of a second wheel parallel to the depth wheel. *Yawing* (moving out of line, moving out of parallel with the direction of movement) can be reduced if the unbalanced side forces causing these "crablike" movements are absorbed by a landside and a furrow wheel or coulter.