A lightweight swing plow for a single donkey: design, operation and the harness

F M Inns[1], R M Shetto[2] and S Mkomwa[3]

[1] Consultant, 53 Alameda Road, Ampthill, Bedford, MK45 2LA, UK
[2] Senior Research Officer in Agricultural Engineering
Ministry of AgricultureTraining and Research Institute, Uyole, PO Box 400, Mbeya, Tanzania
[3] Managing Director, SEAZ Agricultural Equipment Ltd, PO Box 2607, Mbeya, Tanzania

Abstract

A lightweight (12 kg) swing plow and associated harness were designed specifically for use by a single donkey. The primary objectives were to take advantage of advances in technical understanding of the principles of plow and harness design, and of modern materials and construction, to produce a low-cost, easily operated plow matched to the pull capability of a single donkey, using a donkey-friendly harness that could be constructed cheaply and easily. The design was developed using a simple theoretical relationship which indicates that plow draft is a function of the vertical force acting on the plow (mostly plow weight) and the angle at which it is pulled (a function of harness design and adjustment). Field trials to investigate this proposition showed that the draft of the plow in sandy-loam soils was halved when the angle of pull was raised from 20º to 30º. On-farm evaluations of the new plow in Tanzania indicated that pack donkeys with no previous experience of draft work had no problem in adapting to plowing. The plow was easily adjusted and controlled to give acceptable tillage at a depth of about 10 cm without the need for depth wheel or skid. The light weight and ease of control were particularly appreciated by lady farmers. The principles involved in the design of the single donkey plow are readily applicable to the development of easily controllable swing plows matched to the continuous pull capability of other draft animals.

Basic concepts

Interactions between the draft animal and the implement it is pulling

The force interactions between the draft animal, its harness, the implement it is pulling and the operator must be optimized if the animal draft cultivation system is to achieve its full performance potential. The main forces and the relationship between them are illustrated and defined in Figure 1.

A major problem with animal drawn cultivation implements has always been the necessity of adjusting the draft to a reasonable level for the available animals. If the necessary draft reduction could not be achieved by adjusting or modifying the implement it is necessary to increase the number and/or size of animals. The Tillage Implement Draft Equation (H = V/tan ♋; see Figure 1) shows that the draft of an implement having initial draft H can be reduced by reducing the effective vertical force V and/or by using a steeper angle of pull.

Evolution of the swing plow

In the past plows were very heavy; in the 1840s single furrow plows weighed about 100 kg (1000 N) for wheeled plows and about 60 kg (600 N) for swing plows (Handley, 1840). Wheels were used to support part of the plow weight, which reduced the effective vertical force (e.v.f. – see Figure 1) and hence the draft, with a corresponding reduction in depth of work. Swing plows had no wheels but were fitted with slades (horizontal supporting surfaces which slid along the furrow bottom) to provide support.

By the 1940s the weight of a typical swing plow, such as the Ransome's 'Victory' plow, had been halved, to about 30 kg to 40 kg (300 N to 400 N). The need for support was greatly reduced and could be provided by a heel, in effect a shortened slade, which was usually adjustable so that the degree of support could be varied. The load-bearing wheel was discarded, although a residual

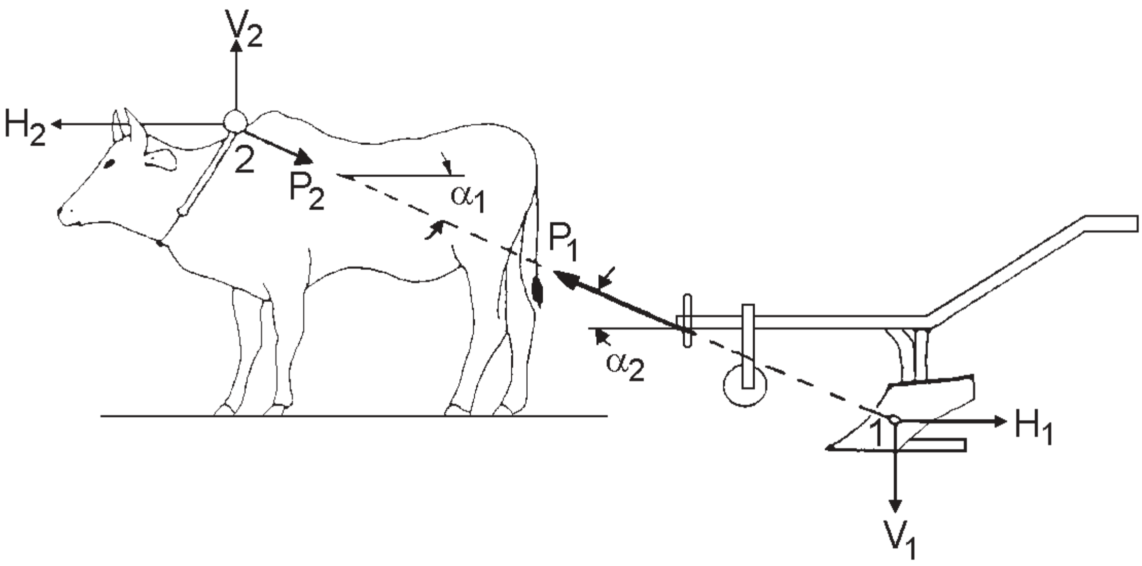


Figure 1: Forces acting on and between a work animal and the plow it is pulling, during steady work on level ground

Forces acting on the plow at the force centre (point 1):

H_1	=	*plow draft*
V_1	=	*effective vertical force (e.v.f.) acting on the plow*
P_1	=	*pull in the plow chain*
♋ $_1$	=	*angle of pull*

H_2 and V_2 are forces exerted by the animal to generate the pull force P_2 in the chain, having the same magnitude as the corresponding forces on the plow

Definitions:

the draft of a plow is the horizontal force with which it resists forward movement.

the effective vertical force (e.v.f.) acting on a plow is made up of its weight (gravity force) and vertical force components from the soil and/or the operator, which may act upwards or downwards. The overall effect must be downwards otherwise the plow will not enter into work.

Support forces are upward-acting force components, which reduce the e.v.f. thereby reducing plow draft and depth of work, intentionally or otherwise.

the pull acting on an implement is the force exerted on the implement from the draft animal(s). It is usually inclined at an angle to the horizontal; this is the angle of pull. The horizontal component of the pull is used to move the plow forward against its draft and the vertical component counteracts the effective vertical force acting on the plow.

The force centre ("centre of resistance") of the plow is the point (point 1 in the diagram) through which the lines of action of the draft, e.v.f. and pull forces pass to keep the plow in steady work, with no tendency to rotate out of its correct working alignment.

The tillage implement draft equation relates these forces: H = V / tan ♋

small nose wheel was retained to help when turning the plow. These changes eliminated the parasitic draft caused by the rolling resistance of the support wheel and greatly reduced the frictional resistance of the heavily loaded slade. The plow became intrinsically more efficient and easier to handle and control.

Today, fifty years later, modern materials and construction enable the weight of a swing plow to be halved again, to about 15 kg to 20 kg (150 N to 200 N) while maintaining or improving its strength. The further reduction in weight, combined with a better understanding of the effect of angle of pull, make it possible to design harness and implement systems that eliminate the need for support forces so that the plow 'floats' with a draft and depth of work that can be adjusted to levels matching the optimum level for the draft animal(s) employed. Significant further improvements in efficiency and user-friendliness are possible, but they have not yet been exploited.

Figure 2: 6" EC1 plow (left) and earlier model of the 4.5" single donkey plow

It was judged that the design, development, operation and farmer evaluation of a plow matched to the work capability of a single donkey would provide a rigorous test and demonstration of the practical application of the principles outlined above.

Development of a plow and harness for use by a single donkey

Designing to meet performance targets

The pull capability of a single donkey was taken as being between 20 kg (200 N) and 25 kg (250 N) over a full working day (based on an assumed body mass between 175 kg and 200 kg and a pull/weight ratio of 12% to 14%). To meet the draft target the plow must be as light as possible and designed to work with an angle of pull up to about 35º. A working width of 115 mm was chosen for the plow body to ensure a reasonable depth of work at the target draft. Plow geometry was carefully arranged so that the plow could be adjusted to run in a balanced condition with pull angles from 20º to 35º, thus ensuring that only the minimum of corrective action would be needed by the operator to produce high quality work.

The single-donkey plow (Figure 2) was manufactured by Project Equipment Ltd, UK. Its basic construction was similar to the company's EC1 plow which had been used previously to validate in practice the theoretical relationship between draft and angle of pull (Inns and Krause, 1995). Plow weight was 12.2 kg (120 N).

A breastband harness was taken as the basis for the harness design. The arrangement shown in Figure 3 provides a wide range of adjustments, allowing it to be fine-tuned for the conformation and comfort of the individual animal. The design maintains the simplicity and low cost of a widely used traditional design which could be modified very simply to adjust the angle of pull by using a length of rope to provide a variable length hipstrap, as shown in Figure 3.

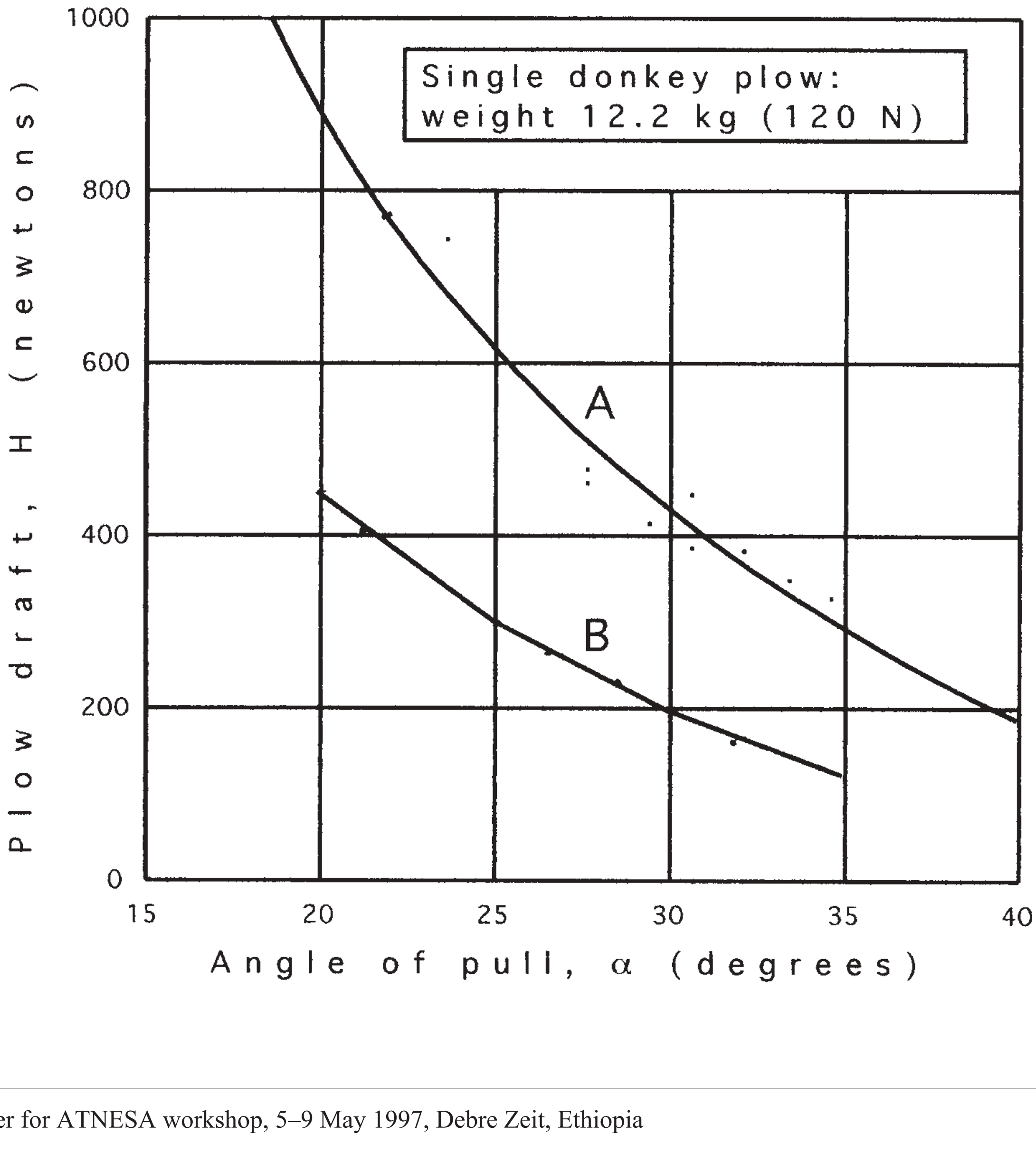
Testing the field performance

Field trials were undertaken with the plow and harness in Edinburgh and Nsalaga, (Scotland and Tanzania respectively), using the draft measuring equipment and procedures outlined by Inns and Krause (1995). The plow was used without wheel or skid and was adjusted carefully to run level and in good balance for each pull angle so that the only forces which the operator needed to apply were small correctional ones to maintain working accuracy. The procedures for setting the plow and harness are outlined in Appendix 1.

The relationships between plow draft and angle of pull for the two locations are illustrated by the two regression lines in Figure 4. The lines do not coincide, probably because the e.v.f. varies with

Figure 3: Breastband harness with variable length hipstrap to provide an adjustable angle of pull from 20° to 35°

Figure 4: Variation of draft with angle of pull: results of field trials in Tanzania and Scotland



the bulk densities of the soils in the two locations, the bulk density of the moist Scottish soil being higher than that of the dryer soil in Tanzania. In both cases the plow draft is halved when the angle of pull is raised from 20º to 30º. It should be possible to achieve the target draft of 200 N to 250 N with a pull angle between 27º and 30º in a less dense soil (such as Nsalaga) and nearly possible (300 N) at 35º in a medium density soil (such as Edinburgh). Conventional breastband or split collar harnesses, for which the angle of pull is about 20º, would cause draft forces of 450 N and 900 N respectively, well beyond what a single donkey could manage, even for a very much shortened working day.

Preliminary farmer evaluation in Tanzania
Preliminary field trials and farmer evaluations of the single donkey plow were undertaken in May 1995 in cooperation with the Ministry of Agriculture Research and Training Institute (MARTI), Mbeya, Tanzania, benefiting from the Institute's extensive local contacts with small scale farmers using draft animal power (oxen, not donkeys). Fields were chosen by the farmers from those in need of cultivation, and therefore represented a range of local conditions.

Although donkeys were kept by the farmers visited they were used only as pack animals and were not accustomed to work as draft animals. A harness was borrowed from MARTI and used in conjunction with a loop of rope to form a hip strap, as shown in Figure 5. The donkeys accepted the harness readily and it was possible to put them to work immediately.

Farmers (and their visiting neighbours) were initially skeptical of the work potential of such a small and light plow but, at the end of some hours work, during which the plow was tried by a number of people, they were satisfied (and somewhat surprised) with the quality and quantity of its output. They had no problems in handling the plow without depth wheel or skid but tended to control it by force rather than finesse, probably as a result of their experiences with heavier and more demanding equipment. An aggressive approach is not necessary – a lady farmer controlled the plow with gently exercised precision.

Subsequent farmer evaluations
Further farmer evaluations were undertaken in Tanzania during August 1995. A total of 14 farmers owning donkeys were contacted and they evaluated both the light plow and its associated

Figure 5: Farmer evaluation of the single donkey plow using a simple adaptation of a locally made breastband harness

Figure 6: The single donkey plow is easily raised out of work for turning etc by lifting or pulling on the handles

harnessing arrangements. The evaluations were made in Galula and Magamba villages in the lower Rukwa valley, where donkeys are extensively used for transportation, and Msia village in Mbozi district which presently has very limited use of donkeys. The donkeys are mainly used for pulling carts, generally using the double neck yoke harness. The use of a breastband h arness is not common and the majority of the farmers were not aware of the harnessing systems, except for one farmer in Njelenje village who had tested the plow in May 1995.

Most of the plow testing was undertaken in August when the soil was dry. In a few cases farmers provided some valley bottom fields which were a little bit moist. Thus in general the field conditions were not the most appropriate as in some instances the soil was hard, restricting the depth of plowing, though many farmers selected fields with relatively lighter soils.

Ease of adjustment and use

- All farmers appreciated the lightness of the plow which made it easy to control. This was an added advantage when turning as the plow could be easily held out of work (Figure 6).
- The adjustments on the plow were few and the farmers felt that they could easily manage them.The adjustable handle allowed operators of various heights to work comfortably without too much bending. The smaller handles enabled a better hand grip making the plow even more controllable, as it could be held firmly and comfortably.
- Many farmers observed that the vertical hake had too many holes for depth adjustment, some of which were unnecessary as the plow might sink too deeply in the soil with the donkey barely pulling it. The extra holes were in any case for experimental purposes and the plow is now made with fewer holes.
- When the skid was not used, there was a tendency for the plow to pitch forwards, lifting up the share point. The operators responded by pressing the handles to exert more force and hence maintain the depth of cut. Rarely did the farmers attempt to adjust the hitch point. Many of them still felt that the use of a depth wheel could make the plow more controllable and maintain an even depth of plowing. Correct adjustment of the hitch point should cure this problem (see Appendix 1).
- Many farmers were of the opinion that the mouldboard and share should be in separate pieces and not one since the rate of wearing for the two parts are different. The mouldboard lasts three times longer than the share. Having the two in one piece would mean higher replacement costs.However, we believe that the combined share/mouldboard is most efficient, since it can be fastened to the handle with only two bolts. If separated the two components would require four bolts, adding to the cost and complexity.

Performance

- The quality of work was satisfactory, with good inversion of the soil and trash coverage, especially where the soil was relatively moist. However, where operators were unskilled and donkeys were not well trained there was poor overlapping of the furrow slices. Training and experience of donkeys and farmers should overcome this problem.
- The depth adjustment (vertical hake) performed satisfactorily. However, many farmers still thought that depth should be adjusted by using the nosewheel. Demonstration, training and experience should convince farmers that a correctly adjusted plow is easier to control without a nosewheel or skid. Removal of the provision for attaching a skid will hasten the process!
- Many farmers observed that the field capacity (rate of work) was rather low because of the small width of cut. This necessitated more passes and hence more time to plow an acre compared to the commonly used 9” UFI plow. Farmers are realists but this does not stop them from dreaming of miracles! The 9” plow would need at least two oxen to pull it.

The manufacturers viewpoint

Raw Materials

Availability of raw materials is one of the most significant constraints to local manufacturing of the single donkey plow in Tanzania. Most of the materials are not locally available and have to be imported. However, importation of small quantities of raw materials is expensive. This would affect the final price of the plow especially at the beginning when sales would be low because of limited demand. Undoubtedly this is a severe infrastructure problem in many countries. Most governments have only paid lip service to solving it – can private enterprise do better?

Ease of Manufacture

The simple design of the donkey plow enables easy manufacture at any workshop equipped with a 40 tonne press. SEAZ Agricultural Equipment Ltd, Mbeya, and other companies including Zana Za Kilimo, Mbeya and Ubungo Farm Implements (UFI), Dar-es-Salaam have adequate machines and technical knowledge to undertake local manufacturing.

Farmer acceptance

The single donkey plow is a new product in the market hence acceptability may not initially be high. Together with the plow two other new innovations, ie harnessing arrangements and use of single animals, are introduced. In areas where farmers have sufficient pairs of oxen, the use of single donkeys and smaller plows might not be so desirable. But where farmers have limited resources chances of adoption are greater.

Price

UFI has moved to cost pricing of their plows: the retail price for UFI plows is now TSh 50 000 (approximately US$75) and the lighter single donkey plow (weighing only 33% of the total UFI plow weight) should have a comparative price advantage. As only a single animal is needed, the plow might be a suitable alternative for small scale farmers.

Conclusions

Until now the design of animal-drawn plows has been a slow, trial-and-error process. Most current animal-drawn cultivation implements belong, practically unchanged, to a past era. This paper considers the case of a single-donkey plow to demonstrate how plow design can be brought into the modern age by an understanding of the simple force systems acting on and between animals, implements and operators, thus speeding up the development of implements and harnesses to match the capability of particular animals and animal teams. The fundamental role of the harness as an integral part of the animal draft cultivation system, and the need to consider it as such, is conclusively demonstrated.

The development work described has led to a better understanding of factors involved in plow operation and adjustments.Existing advice is often contradictory and may not conform with operators' experiences. Many of the conflicts can be explained and resolved using the Tillage Implement Draft Equation (Figure 1) for guidance. The basic force relationships also point to the need for a fundamental review of testing procedures for animal-drawn implements.

Based on experiences with the single donkey plow and harness it is possible to make rational specifications for the leading performance-related features for modern implements and harnesses designed to match the work capabilities of various animal combinations, as follows:

- single donkey: 4.5" (115 mm) body, weight 10 kg to 12 kg, angle of pull variable between 20º and 30º / 35º
- single ox: 6" (150 mm) body, weight 15 kg to 17.5 kg, angle of pull variable between from 20º and 30º /35º
- pair of oxen: 9" (230 mm) body, weight 16 to 18 kg, angle of pull variable between 15º and 25º

These estimates relate to lightweight 'floating' swing plows with no need for a depth wheel, nosewheel or skid.

References

Handley H, 1840. On wheel and swing plows *Journal of the Royal Agricultural Society of England*, 1: 141-147.

Inns F, 1990. The mechanics of animal draft cultivation implements, part 1, chain pulled implements. *The Agricultural Engineer* 45 (1): 13-17.

Inns F and Krause P, 1995. Experiments to investigate the effect of angle of pull on the draft of a chain-pulled swing plow. *Draught Animal News*, 22: 2-6. Centre for Tropical Veterinary Medicine, University of Edinburgh, UK

Acknowledgments

The authors are grateful to Alan Stokes of Project Equipment for supplying the prototype plow used in this work; to Dr M A M Msabaha, Zonal Director of Research and Training, Southern Highlands Zone, Mbeya, Tanzania for his keen interest and support and to numerous farmers and farm workers in the Southern Highlands Region who participated in the evaluation. F Inns is grateful to the Leverhulme Trust for the award of an Emeritus Fellowship which enabled him to contribute to this investigation.

Appendix 1

Adjustment procedures for setting a lightweight swing plow into work

Plow adjustment aims at getting the plow to run 'sweet and level' so that:

- the body runs level with correct clearance under the share and body. This is the most efficient attitude for a mouldboard plow, giving the greatest useful soil disturbance for least draft. Get to know the correct 'set' of the plow — what it looks like when the body is running at its most efficient attitude. When the plow has a straight beam it usually, but not always, runs parallel to the ground surface.
- the operator needs to apply only the slightest of forces at the handles, and solely for corrective action. Guide the plow — don't fight it!

Note:A lightweight swing plow does not need a nosewheel or skid, which only adds unnecessary weight, complication and cost. If one is fitted *take it off*!

Force centre ('centre of resistance')

The force centre is important to correct plow setting. Its position is closely associated with the plow's centre of gravity and may be found with reasonable accuracy as shown below (in fact the force centre is not a fixed point but its position varies only slightly and probably less for a lightweight swing plow than for a heavier one).

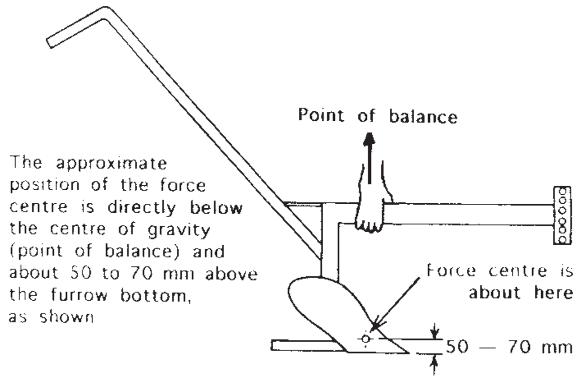


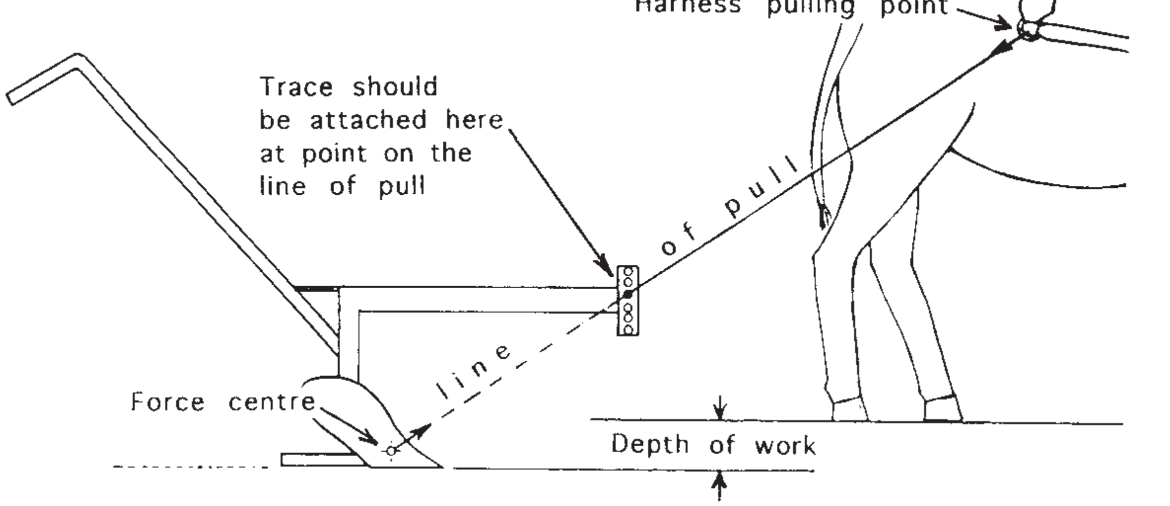
Figure A1: Finding the centre of gravity and position of the force centre

Initial setting into work

Put the plow in its correct working position relative to the draft animal:

- fore and aft position depends on the length of the traces, which should be as short as possible without interfering with the animal's leg movements;
- plow is set into the soil at approximate working depth and with body level;
- the animal should walk on the land as close as possible to the wall of the last furrow.

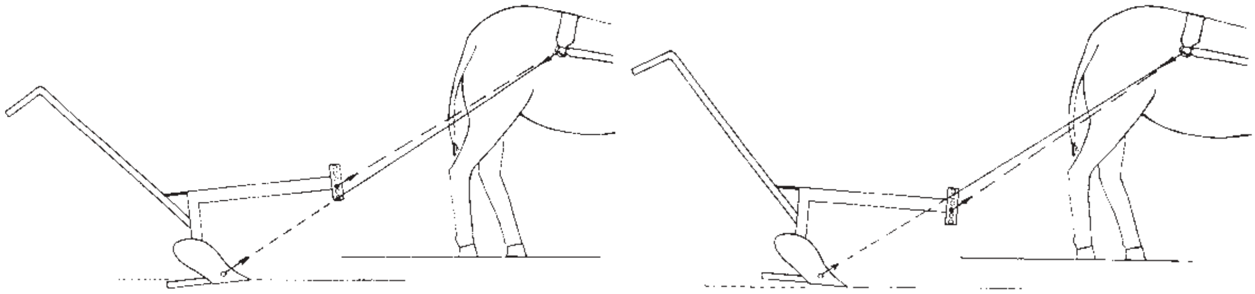
Figure A2: Adjusting attachment of plow traces to coincide with required line of pull



Assess the required line of pull.
This joins the pulling point on the harness and the force centre on the plow. The traces must then be attached to the plow hake or regulator in a position which coincides with the line of pull. This is fundamental, but all is not lost if it is not quite correct first time, as it can be 'fine tuned' later (see below). The recommended procedure is to move to a position about 10 m to the side and square on to the plow. Sight along a line at plow level; visualize the line of pull, noting the position where it intersects the hake/regulator. Attach the traces at this point.

Fine tuning the plow adjustment

Good plowing demands that the plow maintains its correct attitude. The plow body is then in its most efficient working setting and the plow should run virtually 'hands off'. Fine tuning may be needed to make the plow run level. The rules are easy (provided there is no nose wheel or skid to interfere with the adjustment):



Problem: plow runs nose up

Solution: attach the traces to a higher point on the regulator. This will pull the nose down to meet the line of

Problem: plow runs nose down

Solution: attach the traces to a lower point on the regulator. This will pull the nose up to meet the line of

Figure A3: Fine tuning the plow attachment to ensure level running

Make adjustments as above until the plow runs level. Allow no interference from nosewheel or skid.

Setting a reasonable work load for the animal

If the draft is too high for the animal in use, the pulling point should be raised (steeper angle of pull) to reduce the draft, and *vice versa*. Hake/regulator adjustments must be reset when the angle of pull is changed.

Making light work for the operator

When correctly set the plow should run virtually 'hands off' in uniform field conditions. Forces applied to the handles should be small and infrequent, to deal with local variations in field conditions which may cause the depth of work to vary. If a continuous force has to be applied the plow is incorrectly set. Find out what is wrong and correct it.

Adjusting the angle of pull

The most effective way of adjusting the angle of pull is to change the height of the pulling point on the harness (adjustable hip strap) and readjust the attachment point. Changing the regulator is *not* an effective way of adjusting the angle of pull. The regulator should be used:

- to ensure that the line of the traces coincides with the required line of pull; and
- for fine tuning to ensure that the plow is running level.