

1 **Effect of Side-Wings on Draught: The Case of Ethiopian *Ard* Plough (*Maresha*)**

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23
24
25 **Abstract**

26

27 Ethiopian farmers have been using an ox-drawn breaking plough, known as *ard* plough –
28 *maresha*, for thousands of years. *Maresha* is a pointed, steel-tipped tine attached to a draught
29 pole at an adjustable shallow angle. It has narrow side-wings, attached to the left and right side
30 of it, to push soil to either side without inverting.

31 The aim of this paper is to explore the effect of side-wings on draught using a field soil bin test
32 facility. To this end, a mobile and an *in-situ* soil bin test system, for online measurements of
33 draught, was designed and developed. This research considered tool geometry (*maresha* plough
34 with and without side-wings) and rake angle (shallow – 8°, medium deep – 15°, and deep – 24°,
35 representing primary, secondary and tertiary tillage processes in Ethiopia, respectively).

36 *Maresha* plough with side-wings has greater contact area, between the moving soil and tool, than
37 its wingless counterpart. When the ploughshare surface and soil slide relative to one another, the
38 draught expected to increase with contact area, as adhesion and friction resistance increases with
39 area. However, experimental analysis indicated that the *maresha* with side-wings required less
40 draught compared to *maresha* without side-wings ($p < 0.001$). This might be attributed to the
41 effect of side-wings on crack propagation by a wedging effect to enhance and facilitate
42 subsequent ploughing.

43 This paper also dealt with the effect of rake angle on draught. Though the depth setup was
44 getting smaller $d1 < d2 < d3$ for the successive tillage runs, analysis showed increment in draught
45 force ($p < 0.001$) with rake angle. This might be attributed to higher soil compaction that comes
46 with depth and downward force resulting from repeated use of *maresha* every season to the same
47 depth for thousand years.

48 Although more and rigorous studies should be undertaken considering soil, tool, and operational
49 parameters to arrive at conclusive results, this paper gave some insights regarding effect of side-
50 wings on *maresha* plough and rake angle on draught. This shows that there is still room for
51 improvement of *maresha* plough geometry for minimum draught requirement and optimum soil
52 manipulation.

53

54

55 **Key words:** *Ard*, Data acquisition system, Depth, Draught, Mobile and *in-situ* soil bin, *maresha*,
56 Rake angle, Side-wings.

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58

59 **1. Introduction**

60

61 Various researchers have undertaken studies on effect of plough share including its component
62 attachments' contributions on draught requirement and soil loosening.

63 The two types of tine design are usually referred to as narrow tines and winged or sweep-type
64 tines (Spoor, 2006). For compacted surface layers, there is likely to be a need to reduce the
65 confining resistance ahead of the deeper tines; this is achievable using shallower narrow tines
66 working ahead of deeper tines, which preferably should be winged (Spoor, 2006). Spoor and
67 Godwin (1978) investigated deep loosening of soil by rigid tines, the attachment of wings to the
68 tine foot and the use of shallow tines to loosen the surface layers ahead of the deep tine increases
69 soil disturbance particularly at depth, reduces the specific resistance, increases the critical depth
70 and allows more effective soil rearrangement. With sweeps or wings attached to the sides of
71 many of chisel tines, subsoilers, slant tines and oscillating tines, the overall soil disturbance
72 increased for a minimal increase in energy expended (Smith, 1973; Trousse and Humbert, 1959;
73 Balaton, 1971; Lindner, 1974; Schulte, 1974; as cited in Spoor and Godwin, 1978).

74 Raper (2005) showed subsoilers with straight shanks required higher tillage draught compared to
75 the bentleg shanks. The SDN subsoiler shank (straight shank, Deere, narrow point) required 9.25
76 kN, which was the largest draught required, while the smallest draught of 5.85 kN was measured
77 for the BBP shank (Bentleg, Bigham Brothers, Paratill).

78 Marandi *et al.* (2010) used soil bin incorporating a carriage having capable of testing three
79 prototypes of tools in a test run. Georgison (2010) investigated the effect of various settings on
80 tool loading to improve the design of the soil engaging components of a rotary tine aerator.
81 Awad-Allah *et al.* (2009) investigated the dynamics of single and multiple tines at different
82 cutting speeds and depths with and without an added vibratory motion. Ranta *et al.* (2009)
83 analyzed the influence of the kinematic regime of discs in different soil conditions on the soil
84 bed quality. Marakoglu and Carman (2009) evaluated the effects of design parameters of a
85 cultivator share on draught and soil loosening in a soil bin, described by Carman and Dogan
86 (2000). Dedousis (2007) investigated the soil forces and disturbance from different disc
87 geometries and shapes using soil bin developed by Hann and Giessibel (1998). Under the same

88 set up, Vozka (2007) determined draught, area of disturbance, and specific resistance of the
89 selected implements.

90 Sahu and Raheman (2006) predicted the draught requirements from the knowledge of the
91 draught requirements of reference tillage tools in a reference soil condition, in which the setup
92 included soil processing system. Mamman and Oni (2005) used a soil bin facilities to determine
93 the effects of design parameters (slide and nose angles) and operating parameters (soil depth and
94 tool travel speed) on the draught of model chisel furrowers. Durairaj and Kumar (2002)
95 measured the forces acting on moldboard ploughs at six degrees of freedom, which used Clyde
96 (1936) as a basis. Niyamapa and Salokhe (2000a&b) studied the force requirement, pressure
97 distribution, and soil disturbance and force mechanics under vibratory tillage tools.

98 Manuwa (2002), Manuwa and Ademosun (2007), and Manuwa (2009) investigated the influence
99 of soil parameters on draught. Manuwa and Ajisafe (2010), then, developed an overhead gantry
100 to enhance system versatility with better working space by saving the time and labor required for
101 soil preparation and experimentation. Rosa (1997) developed a monorail system, capable of
102 driving soil tools – narrow tools – at a maximum steady speed of 10m/s under load and a
103 maximum draught of 1.5KN. Elliptical, triangular and flat tool shapes presented the lowest to
104 highest draught requirements, respectively. The system was retrofitted to a small 10m long linear
105 soil bin, yet was capable of maintaining target tool speeds of 0.5–10 m/s over 1 to 3 m distances
106 (Rosa and Wulfsohn, 2008).

107 Benard (2010) applied the concept of bionic non-smooth surface to disc ploughs and
108 experimented to examine the effects of different bionic units on reducing soil resistance. Qaisrani
109 (1993) and Qaisrani *et al.* (1992&2010) applied dung beetle having a number of small convex
110 surfaces made of ultra high molecular weight polyethylene (UHMW-PE) and stuck on the
111 surfaces of mouldboard plough at an angle of 62° with the horizontal - based on the findings of
112 Suminitrado *et al.* (1988) that most of soil movements on the plough surface happen at an angle
113 of 62° . Experiments showed that the modified ploughs had better scouring properties and
114 required less draught than conventional tools.

115 Numerical Simulation of Soil-Tool Interactions were undertaken by using Finite Element
116 Modelling techniques (Mouazen and Nemenyi, 1999; Plouffe *et al.*, 1999 a & b, Ibrahim *et al.*,
117 2015) and Discrete Element Method (Bravo *et al.*, 2012), and experimented using soil bin to
118 verify the results calculated.

119 Although several reports on the effects tool design and operational conditions on the
120 performances of different tillage tools and implements by means of a soil bin test system are
121 available in the literature, there is a dearth of information on the Ethiopian traditional *ard* plough
122 – *maresha* including effect of side wings on draught requirement.
123 Hence, this paper mainly aims at undertaking experiments using field soil bin facility to
124 understand the effect of side-wings on draught. Besides, it dealt with the effect of rake angle on
125 draught.

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127

128 **2. Animal drawn implement (Ethiopian *ard* plough)**

129

130 Animal drawn plough (*ard* plough) that differs very little from the old primitive plough is widely
131 in use in Ethiopia. The first ever photograph of an Ethiopian farmer with his oxen and *marasha*,
132 near Senkata (Tigray) in March 1868, is shown in Figure 1 (Nyssen *et al.*, 2011). Most of the
133 components of the traditional implement are wooden except for the ploughshare and metal loops
134 and leather strip or rope, a tying unit. It is a light implement weighing 17 to 26 kgs (Goe, 1987),
135 which makes it handy enough for one person to carry over different terrain (Fig. 2a). A single
136 person can manage to keep the oxen pull the implement along a straight line forward at a
137 relatively constant speed by preventing the oxen from stopping and/or grazing (Fig. 2b). The
138 relative simplicity and regenerative character of animal traction technologies, their strong
139 indigenous nature and simple support systems, have resulted in their integration into small farm
140 systems (Gebresenbet *et al.*, 1997a).

141 Recorded information showed, in 1939 Italians introduced a steel mouldboard plough (Fig. 3) at
142 the small holder level, which was unsuccessful (Nyssen *et al.*, 2011). The Italians concluded that
143 the Ethiopian farmers were conservative and do not want to adopt new technologies (Goe, 1987);
144 and this showed farmers' ideas were not taken seriously and their traditional plough was not
145 studied well. The reasons were its heavy weight, the requirement of complicated adjustments and
146 the higher power requirements than that of the Ethiopian *ard*, especially in soils with higher clay
147 contents (Goe, 1987; Goe and Astatke, 1989; Nyssen *et al.*, 2011).

148 Several organization and institutions have also been trying to modify, introduce, and develop
149 various tillage implements, and to mention some are: FAO in 1950s (Goe, 1987); Alemaya

150 University and Jimma Agricultural Technical School in Ethiopia between 1955 and 1965
151 (Canaday, 1959; UNDP Report); Chilallo Agricultural Development Unit (CADU) later changed
152 to Arsi Rural Development Unit (ARDU) in 1968 (Anon., 1969, 1970, 1971); Institute of
153 Agricultural Research (IAR) of Ethiopia in 1976 (Berhane, 1979); The International Livestock
154 Center for Africa (ILCA) (Astatke and Mathews, 1982; Astatke and Matthews, 1984); The Relief
155 and Rehabilitation Commission (RRC) (Anon., 1981); the Agricultural Implements Research and
156 Improvement Centre (AIRIC) in 1985 (Pathak, 1988); Selam Vocational Training and Farm
157 Implements Production Center (Zaugg, 1992); The National Institute of Agricultural
158 Engineering, Silsoe, UK (NIAE) (Starkey, 1988); Ethiopian Ministry of Agriculture (MOA)
159 (Gebresenbet *et al.*, 1997a); and International Livestock Research Institute (ILRI) (Gebresenbet
160 and Kaumbutho, 1997).

161 Gebresenbet *et al.* (1997a) showed that only a few researchers and farmers have been involved in
162 innovation efforts in animal traction technology in Ethiopia with inadequate grasp of the context
163 of the problems faced by many small farmers. Previous researches on animal drawn tillage
164 implements relied on experience, culture, and trial and error (Gebregziabher *et al.*, 2006).
165 Inadequate knowledge on different tillage tool designs and the indiscriminate use of tillage tools
166 is detrimental to long term improvement of soil quality and crop yields. Hence, a better
167 understanding of soil-tool interaction calls for a systematic approach of researches including
168 utilising indigenous knowledge and incorporating design features of traditional implements in
169 the development process. This is because, designing an implement must take into account the
170 agricultural and industrial systems, within which the implements are manufactured and operated.

171

172

173 **3. Materials and Methods**

174

175 **3.1 Performance of traditional *maresha* plough in Ethiopia**

176

177 With the *ard* design, *maresha* is a pointed, steel-tipped tine attached to a draught pole at an
178 adjustable shallow angle and the soil is not inverted like the case with the mouldboard plough.
179 Instead, the soil is broken or fractured, lifted and then pushed to the sides of the furrow, forming
180 a V-shape furrow (Astatke, FAO) by the two narrow wooden side-wings fitted to each side of the

181 share. The ground between the furrows, which is remained untouched, is broken up by additional
182 ploughings (extra cross-tilling) carried out at different angles across a plot. According to
183 farmers' explanation, side-wings help to increase the soil loosening efficiency (tilled area),
184 helping Ethiopian farmers to meet timeliness for land preparation during sowing seasons.

185 Under typical farm conditions in the Ethiopian highlands, a pair of indigenous oxen is used to till
186 with a draught force requirement of about 1.0 kN (Gebreslasie *et al.*, 2004). Indigenous zebu
187 breeds, weighing 270-330 kg, are mostly used for traction. The average working speed of oxen is
188 0.4 to 0.5 m/s (Geza, 1999), 0.63 m/s (Gebresenbet *et al.*, 1997b), whereas the average speed
189 using horses is 0.75 to 1.07 m/s (Geza, 1999). However, a pair of crossbred cows moves faster
190 (an average of 0.894 m/s) than a pair of oxen, and exerts proportionally greater pulling force
191 when operating in the same field (Gebresenbet *et al.*, 1997b). The difference in speed is
192 attributed to the greater body weight of the cows and the corresponding greater traction that
193 could be generated. The operational speed of draught animals mainly depends on several factors
194 such as training, animal species, operator, harnessing, the weight of the load to be pulled and
195 climatic conditions (Gebresenbet *et al.*, 1997b).

196 Mouazen *et al.* (2007) found different contributions of each ox to the total traction with oxen of
197 unequal strength. The stronger ox moved faster than the weaker ox, creating an asymmetric
198 position of the yoke. In this situation, the weaker ox had to work harder - by spurring to walk a
199 head of the stronger ox - to overcome the force transferred from the strong ox and correct the
200 asymmetric position of the yoke.

201 Hence, the difficulties experienced in experiments on animal drawn implements due to unequal
202 oxen strength and differences in pace of walking (Mouazen *et al.*, 2007), uncontrolled implement
203 behaviour, and field conditions, thus, calls for a systematic approach.

204

205

206 **3.2 Soil Bin Test System**

207

208 The new tillage systems and the need for improved energy efficiency of tillage operations
209 emphasize optimizing tillage tool design. Development of an efficient tillage tool for optimum
210 soil manipulation and minimum draught requirement requires a clear understanding of the
211 interface between soil and tillage tool supported by experimental and theoretical analyses

212 (Plouffe *et al.*, 1999 a & b; Mouazen and Neményi, 1998). These methodologies could
213 significantly assist in optimizing the implement design and operational conditions aiming at
214 minimum draught requirement and optimum soil manipulation performance. Despite continuous
215 development of the theoretical description of interaction processes between soil and tillage tools,
216 experimental approach is still irreplaceable not even the more and more intensive contribution of
217 the newest software, could change this.

218 The soil bin test system, an experimental verification, allows the measurement of different soil-
219 tool interactions. Soil bin facilities vary in scope from small indoor bins to large outdoor soil
220 bins, depending on the objectives for which they are developed, space available, energy
221 requirement, and financial constraints (Wismer, 1984). Soil bin systems could be straight or
222 circular, movable with stationary tools or stationary with movable tools (Durant *et al.*, 1980).
223 Design and experimentation with a soil bin can be effectively accomplished only if the complex
224 interaction between the soil and the machine/tool is clearly understood (Al-Janobi and Eldin,
225 1997).

226

227

228 **3.3 Animal Drawn Plough in Soil Bin**

229

230 Although there is no information to research linking between *maresha* plough and soil bin
231 experimentation in particular, there is little research on animal drawn implements other than
232 *maresha* plough using soil bin test system. Aikins *et al.* (2007) developed an ox-drawn ridging
233 plough using the Godwin-Spoor narrow tine soil force prediction model, and compared
234 predictions with measurements of draught and vertical forces, and a cross-sectional area of soil
235 disturbance. Loukanov *et al.* (2005) experimented with animal-drawn mouldboard plough to
236 investigate effect of enamel coating on specific draught. Gebresenbet (1995) used a soil bin to
237 measure the forces acting on a curved tool, and attempted to develop empirical prediction models
238 of draught.

239 The few researches undertaken on animal drawn tool in an indoor soil bin facilities, i.e., with
240 imported (disturbed) soil, thus, miss out the real-life situation where the plough interacts with the
241 soil in its natural configuration and its spatial variability.

242 Taking account of challenges facing researches on animal traction tillage implements, along with
243 the lessons drawn there from, and taking into account energy needs, soil variability and financial
244 constrains, a mobile and an *in-situ* soil bin test facility was developed, and discussed in the next
245 section.

246

247

248 **3.4 Development of a mobile and an *in-situ* testing device**

249

250 There are no specific theories on determining the dimensions of a soil container. In general
251 terms, soil bins can be classified into large-scale soil bins and small-scale soil bins. The size of
252 the soil bin influences the type of testing, the amount of data collected, and the number of test
253 tools per test run. The significant difference between a large-scale and a small-scale soil bin is
254 the overall length of the soil bin (Mahadi, 2005). Therefore, one can classify any soil bins longer
255 than 20 m as large-scale bins and those shorter or equal to 20 m as small-scale soil bins (Mahadi,
256 2005). Small scale soil bin test systems were designed (Onwualu and Watts, 1989; Durant *et. al*,
257 1980; Godwin *et al.*, 1980; Stafford, 1979; Siemens and Weber, 1964) with lengths ranging from
258 5 to 13 m.

259 Having reviewed soil bin test facilities, a mobile *in-situ* soil bin facility, which could be
260 classified as small scale soil bin test system, was designed and developed to carry out soil-
261 *maresha* interaction study (Fig. 4). A 20m long mobile facility assumed enough to move to
262 another spots. The facility has three parallel rows/rail-tracks, in which, one row is featured with
263 20m long by 1.435m wide. It includes rails mounted on treated wooden sleepers. The rail has a
264 moving carriage, towed by a two-wheel (walking) tractor using steel cable. The carriage is
265 equipped with a test tool, instrumentation, and a data acquisition system for online measurement
266 of draught.

267

268

269 **3.4.1 Drive System**

270

271 Traditional tillage in Ethiopia uses a pair of oxen to pull the ploughing implement. Because of
272 mass inertia of the carriage, a greater force was necessary to trigger initial movement of the

273 carriage, which was heavy to be done by a pair of oxen. Hence, a two-wheel (walking) tractor
274 (15 hp, Model DF, Changzhou Dongfeng Agricultural Machinery Group Co., LTD – DFAM,
275 with CHANGCHAI engine, China) was used, to produce enough draught to conduct the
276 experiments.

277 Compaction induced by vehicle traffic has adverse effects on a number of key soil properties
278 such as bulk density, mechanical impedance, porosity and hydraulic conductivity (Radford et al.,
279 2000; Hamza and Anderson, 2005). One approach that has been proposed to minimise
280 machinery-induced compaction is to utilise controlled traffic systems whereby vehicle traffic and
281 the resulting soil compaction is restricted to either permanent wheel tracks or sacrificial lanes
282 across a field (Reeder, 2002; Hamza and Anderson, 2005). This leaves the cropped area either
283 free of all traffic, or limits the impact of vehicle movement to certain periods in the production
284 cycle (Chamen et al., 2003).

285 Taking into account the problem of machinery-induced compaction and wider wheelbase of
286 power source (two-wheel tractor) than the working width of the testing device, a steel cable was
287 used to pull the carriage with minimum elasticity. With this, experiments were carried out
288 without affecting the initial soil conditions.

289

290

291 **3.4.2 Draught**

292

293 A load cell (from Celtron SQB-5tSS, the Netherlands), having a maximum load of 500 kg and a
294 sensitivity of 2.99mV/V, was used to measure draught. The load cell attached as intermediate
295 member to a spot between the plough shank and steel frame (Fig. 5). Designing sturdy structural
296 attachment (steel frame) was necessary for a proper setup in order to measure the soil resistance
297 on the surface of the tillage tool, without flipping, toppling, and tilting of carriage.

298 To avoid interference of soil with the measurement, the load cell was positioned above the soil
299 surface instead of directly locating behind the ploughshare. As a result, the measuring position
300 differed or at offset from the position of impact, which was considered during calibration. The
301 design took account of allowing for a free contact of load cell with shank of plough, a contact

302 point where the draught is transferred. The free contact allowed for a force transfer without
303 coupling effect, which couldnot be avoided with a solid connection. Besides, in order to allow
304 forces to be absorbed by the frame and ensure proper measurement, the connection of *maresha*
305 plough (shank) with the frame made using rotating end pin. In general, a load cell with free
306 contact at one end with the plough shank (pinned with steel frame) and bolted at the other end
307 (steel frame and the carriage,) was used to measure the total force required to pull the tillage tool
308 through the soil.

309

310

311 **3.4.3 Data Acquisition System**

312

313 The data acquisition hardware (from IOtech, Ohio - USA) was placed in a frame mounted on the
314 carriage together with external 12V battery power source. The hardware included: DBK43A (8-
315 channel strain gage module); Daqbook/2000E (ethernet 16 bit, 200 kHz data acquisition system;
316 including DaqView software); DBK34A (uninterruptible power supply for DC powered
317 systems), and CA-37-3T (expansion cable from Daqbook to DBK modules).

318 A load cell was interfaced with a data logging system and a computer. The wiring between DBK
319 43A and load cell (supplied from different companies) was based on resistance measurement
320 across the bridge points (Table 1).

321 The incoming milli volts (mV) from the load cell was rescaled to give kilograms i.e. with the
322 setup and DASyLab 8.0.1 software package (National Instruments, Ireland), the data sets were
323 read, interpreted, scaled, averaged, displayed and stored on the laptop.

324

325

326 **3.4.4 Calibration of Load Cell**

327

328 Calibration was undertaken to calculate tool draught based on the following assumptions:

- 329 • The location of area of centroid of *maresha* plough is the point (at point '*b*') of
330 concentrated load measured, which is equivalent to the sum of distributed load of the soil
331 resistance.

332 • 'C' stands for the vertical projected distance, in metre, from the area of centroid of
 333 *maresha* plough (point 'b') to the weld connection point of ploughshare and plough
 334 shank 'a'. Let the length between points 'a' and 'b' be L_{ab} , in meter, and rake angle be
 335 'α' in degree.

336 Thus, $C=L_{ab}\sin\alpha$ (1)

- 337 • $L1$, in metre, is the projected distance from point 'a' to centre of the load cell - lower
 338 hole, point 'd'
- 339 • $L2$, in meter, is the distance between point 'd' and Point 'c' (pinned connection of plough
 340 shank on the steel frame)
- 341 • $F_{Load, Resistance}$, in Newton, is load applied for calibration purpose, representing assumed
 342 equivalent concentrated load, soil resistance on Plough
- 343 • $F_{Load Cell}$, in Newton, is force transferred to load cell.

344 For an analytical solution, using schematic and free body diagram (Fig. 6), at static force
 345 equilibrium, the force and moment equations are given by equations 2 and 3, respectively.

346 $\sum F = 0, \vec{F}_{Load, Soil Resistance} - \vec{F}_{Pin} - \vec{F}_{LoadCell} = 0$ (2)

347 $\sum M_{d, LoadCell} = 0, \vec{F}_{Load, Soil Resistance} \times (L1 + C) - \vec{F}_{Pin} \times L2 = 0$ (3)

348 Equating (2) and (3), the force measured by load cell, $F_{Load Cell}$, in Newton, is then given by
 349 equation (4), i.e.,

350 $\vec{F}_{LoadCell} = \frac{F_{Load, Soil Resistance} \times (L1 + L2 + C)}{L2}$ (4)

351 Where C is given by equation (1).

352 In addition to the analytic solution, calibration using software (GageCal) was necessary.
 353 Calibration with GageCal required setting the value of quiescent/Tare to zero for soil-tillage
 354 purpose, however, to measure weight the quiescent/tare value should be the weight of measuring
 355 platform. Name plate calibration was required adjusting for excitation, offset, gain, and scaling
 356 with respective potentiometers without connecting the load cell. Final setup in GageCal required
 357 connecting sensor and adjusting the offset using OFFSET potentiometer. The first offset
 358 adjustment was correcting the internal circuitries offset so that the calibration was as accurate as
 359 possible. Using electronic, GageCal shorted the channel's inputs together. Later on, the offset
 360 was to take into account the actual sensor.

361 There were two modules for scaling i.e. scaling channel with the analog input, and scaling
362 module. In order to avoid double scaling, only the scaling module was used.

363 To minimize the noise in the raw data, hardware and digital filters were also used. The selection
364 of hardware filter was based on experimentation with resistors (Table. 2) by positioning jumpers
365 on DBK43A to filtering position, which activated the analog filter to cancel the noise. The
366 properties of the filter were determined by a resistor, by placing in an electrical circuit.
367 Experimentations showed that the standard filter with a frequency of 13.3Hz lowered most of the
368 noise. Besides, a digital filter module was used to filter the incoming data, and a low pass filter at
369 135 Hz gave better data.

370

371

372 **3.5 Design Parameters: Tool Geometry and Rake Angle**

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374 **3.5.1 TOOL Geometry**

375

376 The two plough geometries considered were: *maresha* without side-wings, and *maresha* with
377 side-wings (Fig. 7).

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379

380 **3.5.2 Rake Angle**

381

382 Depending on soil type and the type of crop cultivated, the land is ploughed 3 to 5 times before
383 planting (Goe, 1999). Gete (1999) explained subsequent ploughings are deeper, except for the
384 last tillage operation, which is done after broadcast sowing. The depth of tilling in the first pass
385 reaches 5-10 cm depending on soil texture, degree of soil compaction, and moisture content. The
386 final pass reaches down to a depth of 20 cm. Considering the three subsequent ploughing, i.e.,
387 primary, secondary and tertiary tillage processes in Ethiopia, in an experimental line, three
388 ploughs were manufactured for each geometry type, i.e., for shallow, primary – α_1 , 8° ; medium
389 deep, secondary – α_2 , 15° ; and deep, tertiary – α_3 , 24° degree (Fig. 8).

390 The respective tool settings could be given by depths: $D1 = 0.1329L$, $D2 = 0.2516L$ and $D3 =$
391 $0.3406L$ where L is length of plough.

392 The study considered successive tillage process in an experimental line, i.e., the 1st tillage run
393 performed on top undisturbed soil layer, however, the 2nd and 3rd successive tillage runs
394 performed on furrows and underneath undisturbed soil layers left by 1st and 2nd tillage runs,
395 respectively.

396 Hence, this paper considered 1st, 2nd, and 3rd tillage runs on undisturbed soil layers having depths
397 of $d1$ ($0.1329L = D1$), $d2$ ($0.1187L = D2-D1$), and $d3$ ($0.089L = D3-D2$), respectively, for
398 analysis, and assumed possible boundary effects are negligible.

399

400

401 **3.6 Experimenting**

402

403 **3.6.1 Experimental Field**

404

405 The experimental field is located at an altitude of 2150 meters above sea level, at the veterinary
406 campus of Mekelle University, on the skirts of city of Mekelle, the regional capital of Tigray,
407 Ethiopia. The experimental soil is classified as Vertisol. Despite their high agricultural potential,
408 Vertisols are generally regarded as marginal soils, among others, high shrink-swell potential
409 (Astatke *et al.*, 2002; Deckers *et al.*, 1998; Potter and Chichester, 1993) which leads to a high
410 incidence of prolonged water-logging during the main rainy season from June to September
411 (Astatke *et al.*, 2002). The soil was covered with grass and there were stones of various sizes in
412 the soil.

413

414

415 **3.6.2 Soil Size Distribution**

416

417 The Bouyoucos Hydrometer method was used to determine the particle size distribution of the
418 soil sample, shown in Table. 3.

419

420

421 **3.6.3 Experimental Layout and Experimentation**

422

423 The overall length, the stretch of the entire soil bin structure, is 20m. Deducting of front and rear
424 pits for starting and ending experiments, the working length of the soil bin is 16m. The
425 experimental design layout considered six experimental rows to have three replicates for each
426 plough geometry types. As shown on Figure 4, the developed soil bin has three rows. Once
427 experimenting on three rows was completed, three rails lines were relocated and installed in
428 reference to the fourth rail to form additional three rail track - rows. Accordingly, experimenting
429 on six rows became possible i.e. by dedicating rows 1, 3, 5 and rows 2, 4, 6 for the *maresha*
430 without side-wings and *maresha* with side-wings, respectively.

431 With two plough geometry types, three rake angles for successive three tillage depths, and three
432 replicates, a total of 2x3x3 experimental runs, equals 18 tillage runs were performed.

433 With such arrangement, the testing device could accommodate even more rows depending on the
434 experimental requirement, number and type of tillage tools to be considered, and available space.

435

436

437 **4. Data Analysis**

438

439 Analysis was undertaken by box plot; and multivariate analysis was undertaken with one way
440 ANOVA using MATLAB tool box. Linear regression and calculation of the Pearson correlation
441 coefficient R and levels of significance (P) were used to measure the degrees of association
442 based on analyses of variance. Histogram also used to see the draught density and distribution
443 with rake angles.

444

445

446 **5. Results and Discussions**

447

448

449 **5.1 Effect of Side-Wings on Draught**

450

451 During a tillage operation various factors can affect energy requirement of a tool. These factors
452 can be categorized in three main groups: (1) Soil parameters:soil physical, mechanical properties,

453 and soil dynamics properties, (2) Tool parameters: tool type, tool shape and size, tool rake angle,
454 tool sharpness, and tool material, and (3) Operational parameters: depth and speed.

455 In addition to soil shear strength properties e.g., soil cohesion and soil-soil friction, draught
456 requirement of soil engaging implements is also affected by soil-material friction. This paper
457 assumed the effect of soil parameters and speed is similar for experimenting with two plough
458 geometries except for soil-tool friction. Soil sliding resistance is made up of friction and
459 adhesion forces that are brought about between the soil and material interface. A large proportion
460 of the energy used to operate tillage tools goes to overcome frictional sliding resistance as soil
461 moves over the tillage tools surfaces.

462 When a material surface and soil slide relative to one another, the frictional resistance of the
463 contact surface must satisfy the Coulomb's equation (5):

$$464 \quad F = CaA + P \tan \delta \quad (5)$$

465 Where, Ca = soil-material adhesion (Pa); δ = angle of soil/material friction (degree), P = normal
466 force on surface (N), F = frictional resistance (N), and A = contact area (m^2).

467 In adhesive soil, the frictional resistance, F , is mainly produced by adhesion and can be
468 minimized if the contact area (A) is reduced (Qian, et al., 1999). When tool surface and soil slide
469 on one another, the frictional resistance expected to increase with interfacial contact area,
470 according to Coulomb's law of soil shear strength (McKyes, 1985).

471 Considering the contact area between the moving soil and tool, *maresha* plough with side-wings
472 has greater contact area than its wingless counterpart. However, results (refer Figs. 9) showed
473 that *maresha* plough with side-wings required lower draught than *maresha* plough without side-
474 wings ($p < 0.001$) despite the greater moving soil and tool contact area for *maresha* with side-
475 wings as compared to *maresha* without side wings. Thus, the result might be attributed to side-
476 wing shape and its wedging effect, which might helped for crack propagation and facilitate
477 subsequent penetration by the plough share, i.e., reducing the soil resistance ahead of the plough
478 share. This might be inline to the finding with paratill (Raper, 2005). However, other literature
479 showed the opposite results, where smaller draught is recorded for tines without wings. For
480 example, previous studies comparing draught of a wing-subsoiler with that of the same subsoiler
481 geometry without wing showed the former to have about 15% larger draught as compared to the
482 latter (Spoor and Godwin, 1978).

483

484

485 **5.2 Effect of Rake Angle on Draught**

486

487 With the respective rake angle, the tillage depth of undisturbed soil, i.e., $d1$, $d2$, and $d3$, setup
488 was getting smaller for the three successive tillage runs in an experimental line.

489 From the data set, average of replicates was considered for analysis, i.e., 6 averages of 18
490 experimental runs representing 3 depths by two plough geometries.

491 Accordingly, the effect of rake angle on draught was investigated with histogram (Fig. 10) and
492 showed the data density distribution for both *maresha* plough geometries is normal. It was also
493 observed that with successive tillage runs, the data density of draught inclines to higher with rake
494 angle for the respective tillage depths on undisturbed soil layers.

495 This was also supported by multivariant analysis that increase in rake angle resulted in higher
496 draught for successive tillage runs despite the tool depth settings ($p < 0.001$). This might be
497 attributed to soil compaction with depth and downward force of the ploughshare acting on the
498 layer below, because of repeated tillages for thousand years.

499

500

501 **6. Conclusions**

502

503 In the face of numerous reports on studies of the effects of draught on the performance of
504 different tillage tools and implements by means of soil bin test systems, sufficient information is
505 lacking on experiments on the Ethiopian *maresha* plough with a soil bin test system. Besides,
506 there is no information regarding the effect of side-wings of *maresha* plough on draught. .

507 The paper discussed the development of a mobile and *in-situ* soil bin test system, and with
508 experimentation, insights observed on the effect of side-wings of *maresha* on draught, i.e., its
509 wedging effect to enhance crack propagation and reducing the soil resistance ahead of the plough
510 share.

511 Despite the fact that tool depth was getting smaller for the three successive tillage runs in an
512 experimental line, higher rake angle also resulted in higher draught which could be explained in
513 terms of soil compaction that comes with depth, and to downward force resulting from repeated
514 tillages every season to the same depth for thousand years.

515 Hence, this work gave some insights for further investigation on the effect of different tool
516 settings, and sizes and shapes of side-wings on soil failure pattern and draught requirement
517 targeting setting of standards. Understanding of the effect a tool has on a particular soil will help
518 in proper design of the Ethiopian *maresha* plough. Adjustments in plough design can also
519 improve the quality of work enabling a tiller to select a different type of tool for each condition
520 he encounters or wishes to establish.

521

522

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524

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530 **8. References**

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757

758 **9. Figures**

759

760 Fig. 1. Traditional plough: The first ever photograph of an Ethiopian farmer with his oxen and
761 marasha, near Senkata (Tigray) in March 1868. © Royal Engineers of the British Army,
762 reprinted with permission of the King's Own Museum, Lancaster, UK. (Nyssen *et al.*,
763 2011).

764 Fig. 2. Traditional plough, Photo, ILCA collection, Samuel Jutzi and Guido Gryseels (Nyssen *et*
765 *al.*, 2011): (a) Mode of transport, and (b) during ploughing.

766 Fig. 3. Italian mouldboard ploughs imported into Ethiopia (near Mekelle, in 1938). Photo by
767 Guidotti, "Gift of H.E. the Head of State to the inhabitants of Tigray" states the original
768 legend of this photograph obtained from the Istituto Agronomico per l'Oltremare
769 (Florence, Italy) (Nyssen *et al.*, 2011).

770 Fig. 4. A mobile and an *in-situ* soil bin test sytem with three rows: (a) 1, Dataloger and battery;
771 2, Rear carriage unit; 3, Steel frame; 4, Front carriage unit; 5, Rail; 6, Wooden Sleeper; 7,
772 Extension of steel frame for loadcell and plough attachment; 8, Load cell; 9, Plough; 10,
773 Free wheel (wheel gage), (b) 1, Two rails for one line - each with 10m length, forming
774 a total of 20m length; 2, Rail Connector/plate; 3, Wooden Sleeper; 4, Carriage with
775 Implement and data acquisition system; 5, Steel Rope for Pulling Carriage; 6, Two-wheel
776 (Walking) Tractor; 7, Pit for defined experiment with starting and ending, and (c) 1,
777 Carraige; 2, Data logger; 3, Battery; 4, Laptop.

778 Fig. 5. Steel Frame with load cell and pattachment: 1, Steel frame; 2, Load cell; 3, point contact
779 between load cell and plough shank; 4, Plough shank; 5, *maresha* plough without side-
780 wings; 6, *maresha* plough with side-wings.

781 Fig. 6. Load Cell: (a) Schematic of Load Cell Assembly and Acting Forces, and (b) Projected
782 Free Body Diagram (View A-B)

783 Fig. 7. Traditional Ethiopian plough - *maresha*: (a) with side-wings (soil-tool contact surface
784 area $\sim 0.0376\text{m}^2$), and (b) without side-wing (soil-tool contact surface area $\sim 0.0184\text{m}^2$).

785 Fig. 8. Tool rake angle and depth (α_1 , α_2 , and α_3 are rake angles for successive three tillage runs in
786 an experimental line for depths setup of D1, D2, and D3, in which $d1$, $d2$, and $d3$,
787 respectively, are tillage depths of undsisturbed soil layer.)

788 Fig. 9. Effect of tool geometry on draught: Box-plot (WW, with side-wing; WO, without side-
789 wing; 1, 2, and 3 stands for three successive tillage runs, reselectively.)

790 Fig. 10. Effect of tillage depth on draught - Histogram: (a) *Maresha* with side-wings, (b)
791 *Maresha* without side-wings

792

793 **10. Tables**

794

795 Table 1. DBK43A - Wiring and Color differences of IOtech - USA and Load Cell from Celtron,
796 the Netherlands

797 Table 2. Filter and Resistor Relations

798 Table 3. Soil Size Distribution of the Experimental Site

799

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