Effects of conservation tillage equipment configurations on soil disturbance and seedling vigor

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Acknowledgments

Spending eight weeks in a foreign country and conducting research at a world-class institution is intimidating for any recent high school graduate, but it is also extremely rewarding. I learned subject-specific knowledge, but also—and perhaps more importantly—learned to be more independent, understanding, and flexible. Living away from my parents, experiencing a different culture from my own, and adapting to change made me a better version of myself.

But, of course, I must thank several people for helping me grow as a researcher and as a person. First, the World Food Prize Foundation and Ambassador Kenneth Quinn for creating this internship, Crystal Harris for supporting me all summer, and Johanna Braun for coordinating the intern program at CIMMYT. I thank Dr. Jelle van Loon for being an awesome research supervisor and encouraging me to explore interesting ideas, even if they were not in our original plan. I thank Jesús López and Gabriel Martínez for working with me every day. I thank everyone at the machinery development site of CIMMYT's Sustainable Intensification Program for welcoming me there. And I thank my family for always being there for me (including on FaceTime!).

Abstract

Conservation agriculture—which requires constant soil cover, crop rotation, and minimal tillage—has been promoted throughout Mexico as a sustainable way to improve long-term agricultural productivity and lessen environmental degradation. Many researchers have studied the value of this farm management practice, and in this paper, the minimum tillage requirement of

conservation agriculture is of especially great interest because excessive tillage disturbs soil and can worsen erosion and soil health. Farmers who are accustomed to the traditional tillage practices, however, may not accept the idea of minimum tillage, but they may also find strip tillage (a slightly more disruptive method of conservation tillage), more acceptable. Possible improvements in seedling vigor when using strip tillage (as the increased vertical soil disturbance allows for easier root establishment) could also affect farm management decisions. This makes it crucial to compare strip tillage to other forms of conservation tillage and consider its role in conservation agriculture.

Existing studies of soil disturbance have typically been conducted in soil bins and cannot accurately represent the irregularities of actual farmland or the effects tillage has on crops. Few studies have assessed soil disturbance in-field or developed a systematic method of completing such assessment. This study details and implements a systematic method to evaluate the effects of four different configurations of conservation tillage equipment (including one strip-till configuration) on soil disturbance and seedling vigor in actual farms.

This study finds that the strip tiller and planter equipment configuration does not disturb the most soil or promote the most vigorous seedlings. The results show that the cutting disk plus planter configuration has the best combination of a low soil disturbance and high seedling vigor. Before offering recommendations to farmers, it is necessary to replicate the study and to study local farmers' attitudes about the machinery included in this experiment, long-term costs and environmental impact of the equipment configurations, the distribution of stress on the machinery (and how this impacts fuel consumption and maintenance), and whether the results of the seedling vigor tests depend on the crop used. Nevertheless, the insights gained from this study serve as an important starting point for more investigations of Central Mexican farm management practices that have real impact on farmers' lives.

Introduction

About Me

I live in New Jersey, the most densely-populated state in the US, and am now a first-year student at Columbia University in the (crowded and bustling) City of New York. The environment I live in has definitely impacted my interest in food security, as it began with urban farming. In middle school, when the Earth's human population had just reached seven billion and the world's attention was on issues of sustainability, I decided to do something to help fight hunger. I visited a local greenhouse to learn how to actually grow food hydroponically and focused on practical, tangible lessons that I couldn't read about. The high-tech kind of agriculture used there and in places like Singapore and the International Space Station was fascinating.

After hearing about the World Food Prize's youth programs, I considered how a more low-tech version of what I learned could benefit farmers in rural areas. In 2016, I submitted a paper to the New Jersey Youth Institute and was extremely fortunate to have been chosen to attend the Global Youth Institute in Iowa. And the summer before the Global Youth Institute, I traveled to India to test whether my low-tech hydroponics idea could potentially work in real life. The resulting research paper, “Assessment of Electricity-Free Hydroponics in India: A Proof of Concept Field Study,” was published in the peer-reviewed *Journal of Agricultural Science.*

Becoming a Borlaug-Ruan International Intern

Interacting with World Food Prize Laureates, talented peers, and professionals doing the work I aspired to do was so inspiring that I went home and almost immediately started writing my application for the 2017 Borlaug-Ruan International Internship. And just a few short months later—I didn’t get it. But I applied for the internship again in 2018, and by a great stroke of luck, it worked!

I was assigned to work at the machinery development site in El Batán as part of CIMMYT’s Sustainable Intensification Program. At first it was unclear why the World Food Prize would want me to work on machinery, but their decision made sense after just a week in Mexico. My previous research had adapted an innovation to suit a certain environment and target population, and the program I was assigned to does just that by operating at various scales for farms in different environments and of different sizes. It was a perfect match!

About CIMMYT

The International Maize and Wheat Improvement Center was, as a whole, a great place to work. The worldwide acronym CIMMYT comes from the Spanish name for the institution. This fact was (I now realize) an indication of what work at the headquarters in Mexico would be like: global impact rooted in local culture. (Fortunately for me, people welcomed my efforts to learn more about Mexican culture and speak almost exclusively in Spanish.) CIMMYT is also huge—it has projects in over 40 countries, generates up to US$4 billion worth of benefits a year, and focuses on two of the world's major staple crops—but it has also trained over 10,000 individual scientists (plus several Borlaug-Ruan International Interns!) to take knowledge back to their home countries. The lush campus in the mountains is unquestionably beautiful, but it is also a busy experiment station. Experiments being conducted there during my stay include producing wheat for tropical areas, testing different species combinations for intercropping, and—this is where I come in—implementing conservation agriculture.

Conservation Agriculture in Mexico

"Conservation agriculture" refers to a sustainable farm management practice that has three main requirements: constant soil cover, crop rotation, and minimal tillage. Surface residue covering the soil improves water's infiltration of soil, decreases water loss due to evaporation, and protects soil from fluctuating temperatures (Hobbs, Sayre, & Gupta, 2008; Dumanski, Peiretti, Benites, McGarry, & Pieri, 2006). Crop rotation improves soil health by increasing microbial biodiversity and decreasing the risk of disease (Hobbs et al., 2008). Reduced tillage decreases the emission of greenhouse gases by animals and machinery and reduces the energy expended to prepare soil while increasing the amount of organic matter available for plants (Hobbs et al., 2008; Sapkota, 2012).

CIMMYT and the Mexican Secretariat of Agriculture, Livestock, Rural Development, Fisheries, and Food created the Sustainable Modernization of Traditional Agriculture (MasAgro) program to promote conservation agriculture in Mexico. MasAgro aims to increase farmers' productivity and lower their costs and environmental impact. It has seen great success within its innovation hubs and several Central Mexican states, but conventional farmers often struggle to adopt sustainable practices such as conservation agriculture (World Bank, CIAT, & CATIE, 2014; Shiferaw, Okello, & Reddy, 2009). Conventional farmers who regularly till their land may oppose the minimum tillage aspect of conservation agriculture and could potentially find the switch to strip tillage (which is a relatively more disruptive method of conservation tillage) more acceptable.

Objectives

The goal of this study is to evaluate strip tillage as a sustainable option for maize production in the Valles Altos region of Central Mexico. Strip tillage and other forms of conservation tillage are compared in terms of soil disturbance and seedling vigor. Soil disturbance studies are usually conducted in soil bins, as Liu, Chen, and Kushwaha did in 2010 and Solhjou, Fielke, Desbiolles, and Saunders did in 2014, but these are ideal environments that lack the irregularities of real fields (Van Muysen, Van Oost, & Govers, 2006). Few studies, such as that of Van Muysen et al. in 2006 and that of Zhang, Su, and Nie in 2009, have evaluated tillage in normal field conditions.

Methods and Materials

Analyzing soil disturbance

Study area

The experiment was conducted in the M7 plot of land within the CIMMYT campus, using 16 beds that were each 50 m in length and each containing one line of maize. The CIMMYT campus in El Batán, Estado de México is located at 19°31'N, 98°52'W and an altitude of 2249 m (International Maize Report 2005 for CHTHIY, 2005).

Characterizing soil properties

Soil conditions at the time of planting were characterized. Soil samples up to a depth of 30 cm were taken at three points in the field (two corners and the middle) because the field had been under the same treatments for the past several years and the soil was expected to be nearly homogenous. The soil samples were placed in open-top aluminum containers and kept in an oven at 75°C for 72 hours to remove water from the soil. Apparent density was defined as the dry mass of the soil divided by the volume of the instrument used to collect the samples (**Table 1**).

Table 1. Values of mean apparent density of soil at various depths within the soil.

Depth (cm)	**Mean apparent density (g/cm^3)**
0-10	1.26
10-20	1.32
20-30	1.42

The mean gravimetric soil humidity of the soil was also measured by collecting soil samples at various depths at three representative points in the parcel of land, then comparing their humid and dry weights (**Table 2**).

Table 2. Values of mean gravimetric soil humidity at various depths within the soil.

Depth (cm)	**Mean gravimetric humidity (%)**
0-20	14.5
20-40	11.5
40-60	10.6

60-80	12.3

Two repetitions of the measurements of the soil's resistance to penetration were conducted at each of three representative locations (again, two corners and the middle) in the field and averaged (**Table 3**).

Table 3. Values of the soil's resistance to penetration at various depths within the soil. Resistance values are expressed as the extra pressure required to reach a given depth after reaching the previous depth.

Depth (cm)	Mean resistance to penetration (kPa)
10	0.254
15	4.56
20	8.62
25	9.63
30	10.1
35	11.1
40	12.2
45	14.7
50	14.2

The residue coverage of the soil was also estimated. This was done individually for each bed, as it can vary greatly within a single field. Locations for testing were randomly chosen by using a random-digit table and counting off digits by twos, then discarding any numbers that were not within the range 00-49. To estimate percentage, an image of a 0.75 m^2 area of the bed was photographed from 1m perpendicularly above the soil (**Figure 1**). The image was analyzed using the software ImageJ. The original color image was converted to an 8-bit grayscale image (**Figure 2**), then processed to make a binary black-and-white image (**Figure 3**), with the crop residue appearing white and the soil appearing black. The number of white pixels in the image was divided by the total number of pixels to find the percentage of soil covered by crop residue. This technique served only as a descriptive estimate because the residue and soil were similar in color, so color segmentation was difficult. The technique used has a tendency to overestimate the area of crop residue because vertical crop stubble often appeared horizontal in the images take from above. Residue from each bed was then collected in a paper bag, weighed, and placed in the oven at 75°C for 72 hours to remove the water. It was weighed again to find the dry mass. The dry mass was divided by the land area the residue was collected from to find the biomass density. The humid and dry masses were used to find the gravimetric humidity of the crop residue. (**Table 4**).

Figure 1. Original color image of crop residue.

Figure 2. 8-bit grayscale image of crop residue.

Figure 3. Binary black-and-white image of crop residue.

Table 4. Values of biomass density, gravimetric humidity, and percentage soil cover of crop residue collected from each bed.

Bed	Biomass density (g/m^2)	Gravimetric humidity (%)	Percent cover (%)

1	199	61.9	42
2	245	56.9	72
3	139	48.4	47
4	200	36.7	73
5	126	19.7	47
6	166	28.4	48
7	190	24.3	32
8	194	31.0	47
9	224	87.4	49
10	165	44.5	39
11	175	36.6	40
12	208	27.2	41
13	215	25.6	65
14	98.7	7.2	54
15	134	49.3	53
16	162	70.6	63

Planting procedure

Lines 1 through 4 were planted using the configuration cutting disk, chisel tine, and Acraplant planter; lines 5 through 8 were planted using the cutting disk and Acraplant planter; lines 9 through 12 using just the Acraplant planter; and lines 13 through 16 using the Yetter Maverick strip tiller first, then followed by the Acraplant planter. The first two lines dedicated to each configuration were completed without the use of the planter's press wheels, allowing for measurement of planting depth and analysis of the soil profiles, while the last two lines for each configuration were completed with the press wheels intact, allowing tests of seedling germination and vigor.

The speeds of the strip till and seeding machines moving through each bed of soil were calculated by timing how long it took for them to move 10 m. The 10 m-stretch chosen was in the middle of the field so that acceleration due to starting or stopping the tractor at the ends of the beds would not affect the calculated speeds (**Table 5**).

Table 5. Speeds of the machinery moving through the beds of soil.

Beds	Speed (m/s)
1 and 2	0.754
3 and 4	0.750
5 and 6	0.774
7 and 8	0.764
9 and 10	0.830
11 and 12	0.788
13 and 14, strip tiller	0.968
13 and 14, planter	0.792
15 and 16, strip tiller	1.08
15 and 16, planter	0.797

After planting, the depth of planting was measured at 13 locations in the lines that were completed without using press wheels (**Table 6**). The locations for measuring depth were chosen systematically by beginning at one end of the bed and then measuring every 3.8 m.

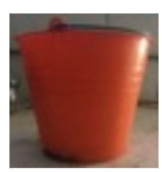
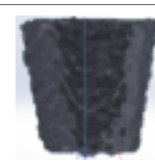
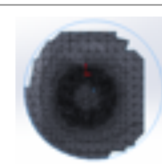
Table 6. Equipment configurations used and mean depth of planting in various lines of maize.

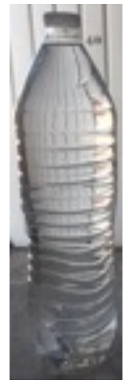
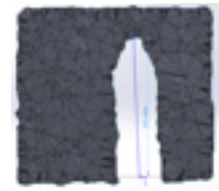
Line	Equipment configuration	Mean depth of planting (cm)
1	Cutting disk, chisel tine, planter	6.9
2		7.9
5	Cutting disk, planter	9.3
6		8.7
9	Planter	8.8
10		8.7
13	Strip tiller → planter	10.6
14		10.7

Validating the Kinect scanner

The Kinect scanner was developed for use with the Xbox 360 video game system (not for accurate 3D scanning for scientific purposes), so its accuracy had to be validated before its use in analyzing soil profiles. To validate the scanner, select dimensions of various household objects of relatively simple 3D structure were measured manually and recorded. A "test plaster" was also created to serve as a close approximation for the irregularly-shaped plasters that the tilling experiment was expected to generate. Using the software KScan3D with the Kinect scanner, the objects were each scanned five times from a distance of 95 cm from the scanner. The scans were then combined and finalized (with low mesh density to allow for faster analysis on the computer) and exported as stereolithography (.stl) files, then analyzed in SolidWorks. The scanner produced fairly accurate average results for all measurements tested except for the diameter of the opening of the bucket (**Table 7**). The relatively low mesh density used likely contributed to some error in measurement, so the scanner would be more accurate when using higher mesh densities.

Table 7. Comparison of dimensions by manual measurement and analysis in SolidWorks. Only Dimension 1 for the side view of the bucket showed a significant ($p > 0.05$) difference in measurement.

Object	Dimension 1 (cm)		Dimension 2 (cm)		Photo	Mesh in SolidWorks
	Manual	SolidWorks	Manual	SolidWorks		
Bucket (side view)	26.5	27.2	23.0	23.0		 
Roll of tape	13.5	13.6	-	-		

Clear plastic water bottle	27.9	27.9	7.6	7.6		 
Test plaster	20.0	20.2	6.1	6.3		 

Analyzing soil furrows

The furrows in the lines of corn planted without the use of press wheels were analyzed to quantify and compare the soil disturbance generated using various configurations of cutting disk, chisel tine, planter, and strip tiller. For each of the eight lines used, three locations (two ends and the middle) were chosen. At these locations, metal boxes of 30 cm width, 40 cm length, and 20 cm depth were slowly pushed into the soil so as not to damage the furrow. Liquid plaster was then poured into the furrow until the furrow was completely covered and the top surface of the liquid was flat. The plasters were then allowed to dry during the afternoon and covered with plastic sheets overnight to protect them from rain and dew. The plasters were removed from the ground after 72 to 120 hours, depending on how quickly they dried. Then, to harden the plasters, they were placed in an oven at 75°C for 24 to 48 hours. Any soil that was stuck to the plasters was carefully cleaned off to reveal the profile of the soil furrows. These profiles were then scanned using the Kinect scanner and KScan3D software. They were exported as stereolithography files and analyzed in SolidWorks. Using SolidWorks, six 2 mm-wide slices of the plasters were generated and converted into two-dimensional DWG (.dwg) files, and the width, depth, and area of the cross-sectional slices were measured in DraftSight. The average cross-sectional area was multiplied by the length of the plaster profile (which was the same as the length of the box the liquid plaster was poured into) to find the mean volume of soil disturbed.

Evaluating seedling germination and vigor

While germination itself could not be monitored underneath the soil's surface, the percentage of seedling emergence from the ground was taken to be a conservative estimate of germination, as some seeds complete the metabolic processes of germination without reaching the radicle elongation stage of visible germination (Bewley, 1997; Ranal & Santana, 2006). The number of seedlings that emerged from the ground was counted daily for ten days to find the seedling emergence percentage.

The vigor of the seedlings that emerged was also assessed using physical characteristics of the plants, as it is believed that the morphological traits of seedlings are strong indicators of their future growth and are frequently used worldwide as indicators of seedling vigor (Puttonen, 1997; Revilla, Butron, Malvar & Ordas, 1999). There are effective destructive and nondestructive methods of assessing seedling vigor (Mattsson, 1996), so both were used and compared in this study. After 35 days of growth, the height (including the leaves) and stem diameter (measured at the site of the first leaf) of 10 randomly-selected seedlings planted using each equipment configuration were measured in-field. The seedlings were then removed from the ground and carefully washed before the roots were weighed.

Results and Discussion

Soil furrows

The soil furrow data from plasters 4, 5, 6, 10, 11, 12, 16, 17, 18, 20, 21, and 22 were discarded because the plasters were severely damaged. The average depth, width, and area of six slices of each plaster (**Table 8**) and for each treatment (**Table 9**) were calculated. Diagrams of the slices of each plaster were also created (**Appendix: Figures 4-15**).

Table 8. Average width, depth, area, and volume of each plaster.

Treatment	Plaster number	Width (cm)	Depth (cm)	Area (cm^2)	Volume (cm^3)
Cutting disk, chisel tine, planter	1	27.4	18.4	269	10,800
	2	24.4	11.0	135	5400
	3	25.2	12.5	151	6040
Cutting disk, planter	7	24.0	10.9	138	5520
	8	19.9	10.1	115	4600
	9	21.7	9.96	115	4600
Planter	13	24.2	9.40	94.2	3770
	14	17.0	7.99	59.0	2360
	15	20.0	7.21	69.4	2780
Strip tiller → planter	19	21.9	8.78	94.3	3770
	23	25.4	11.8	161	6440
	24	22.1	11.0	113	4520

Table 9. Average width, depth, area, and volume of soil furrows when using each equipment configuration.

Equipment configuration	Width (cm)	Depth (cm)	Area (cm^2)	Volume (cm^3)
Cutting disk, chisel tine, planter	25.7	14.0	185	7410
Cutting disk, planter	21.9	10.3	122	4910

Planter	20.4	8.20	74.2	2970
Strip tiller → planter	23.1	10.5	123	4920

Seedling vigor

The mean values for stem diameter, stem height, and total length of roots were calculated for 10 seedlings planted using each equipment configuration (**Table 9**). Configurations that disturbed less than 5050 cm^3 (the mean soil disturbance for the four configurations) were said to have low soil disturbance.

Table 10. Average stem diameter, stem height, and length of roots of seedlings planted using each equipment configuration.

Equipment configuration	**Mean stem diameter (mm)**	**Mean stem height (mm)**	**Mean mass of roots (g)**
Cutting disk, chisel tine, planter	18.0	945	.723
Cutting disk, planter	20.6	1000	1.06
Planter	18.5	930	.784
Strip tiller → planter	20.3	965	.905

The seedling emergence for each was defined according to equation

where is seedling emergence after ten days, is number of seedlings emerged after ten days, and is the number of seeds planted (Adebisi, Kehinde, Porbeni, Oduwaye, Biliaminu & Akintude, 2014). The vigor was then defined according to the equation

where is the seedling vigor index (with higher values indicating greater vigor), is the mean stem height, is the mean stem diameter, is the mean mass of the roots (in grams), and is the seedling emergence after ten days (as defined above). **Table 10** gives the seedling emergence rate and vigor for the seedlings planted using each equipment configuration. Configurations that produced seedlings of 39.1 (the mean value for the four configurations) or higher were said to produce highly vigorous seedlings.

Table 11. Seedling emergence rate and vigor of seedlings planted using each equipment configuration.

Equipment configuration	Seedling emergence rate	Seedling vigor index
Cutting disk, chisel tine, planter	0.953	36.2
Cutting disk, planter	0.967	49.8
Planter	0.923	36.4
Strip tiller → planter	0.790	34.0

The results shown in **Table 9** and **Table 11** indicate that the strip till configuration did not disturb the most soil or produce highly vigorous seedlings, whereas the cutting disk and planter was the only configuration to have both low soil disturbance and high seedling vigor. For farmers in the Mexican highlands, this could suggest that minimum tillage can be highly successful at a relatively low cost (only one planter and a cutting disk is required for the most effective configuration, whereas the strip tillage configuration requires two separate machines). Further study is needed to evaluate farmers' attitudes towards the various configurations tested in this experiment as well as the long-term costs and environmental impact of using the equipment.

Appendix

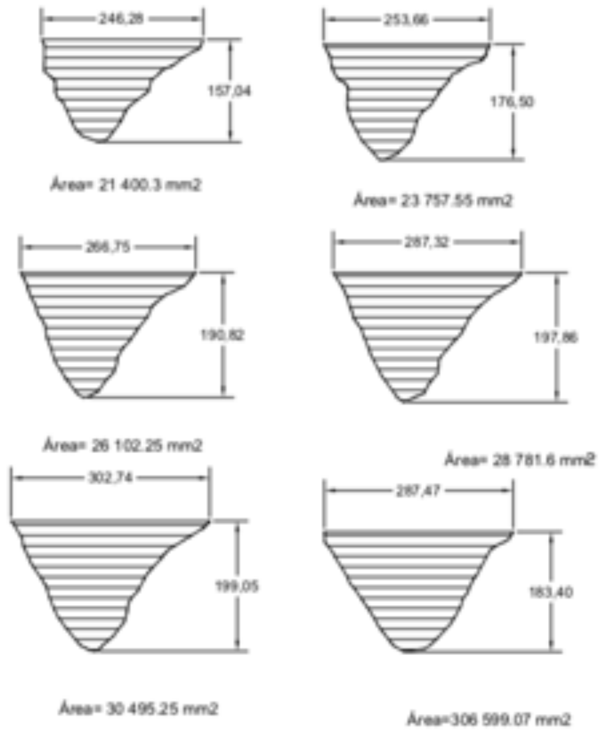


Figure 4. Slices of plaster 1.

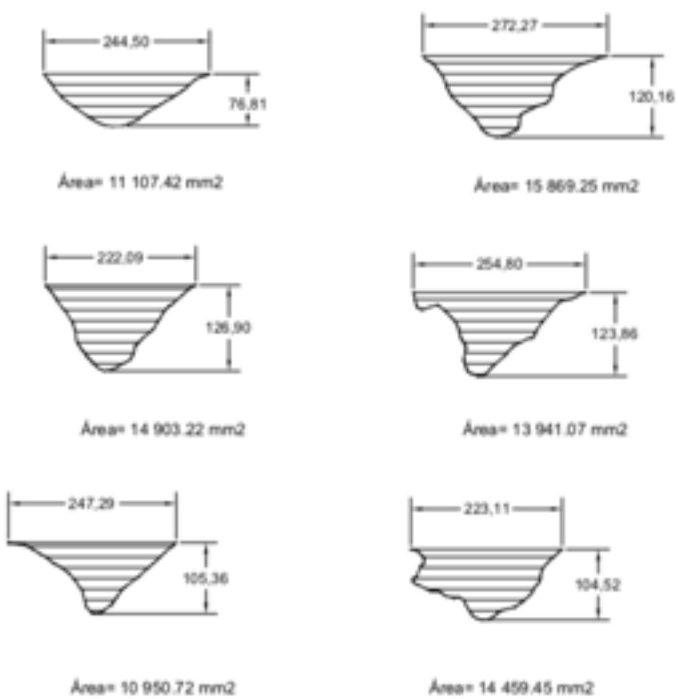


Figure 5. Slices of plaster 2.

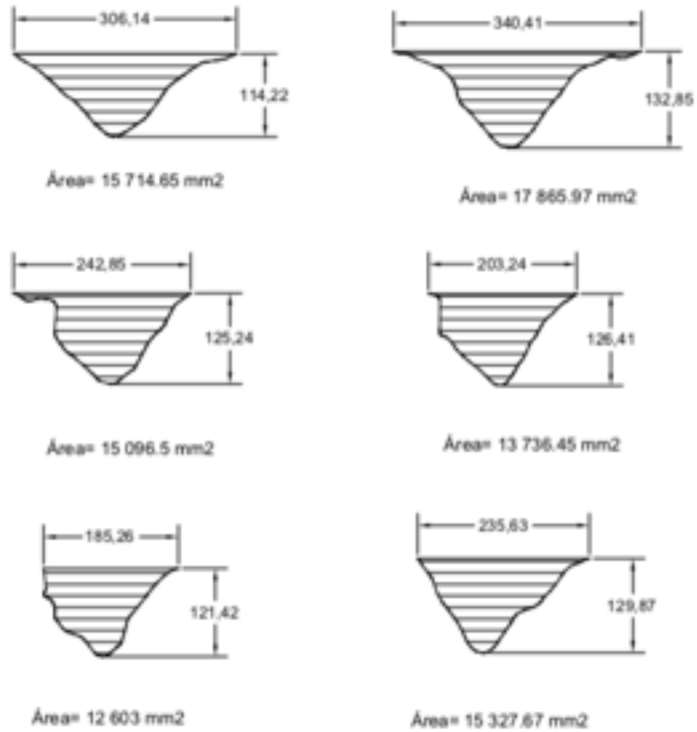


Figure 6. Slices of plaster 3.

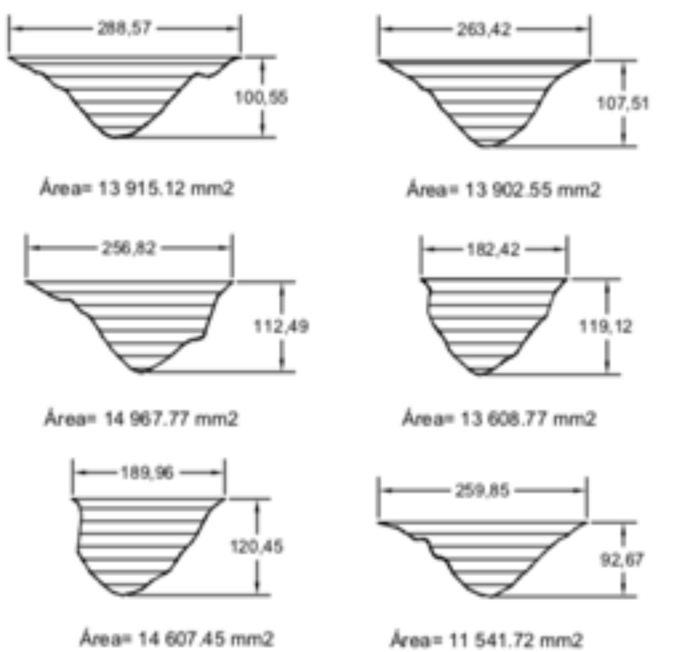


Figure 7. Slices of plaster 7.

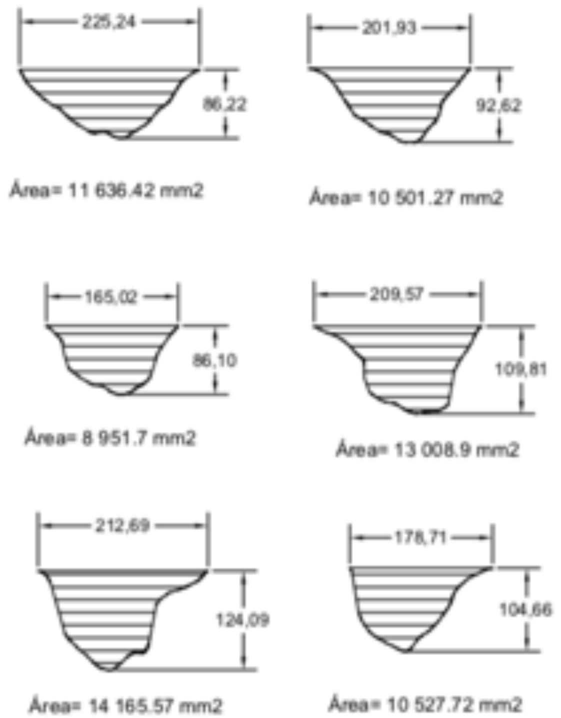


Figure 8. Slices of plaster 8.

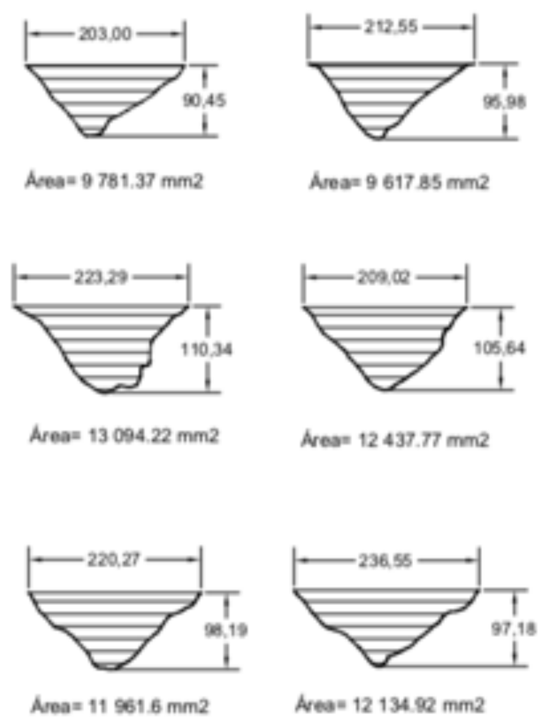


Figure 9. Slices of plaster 9.

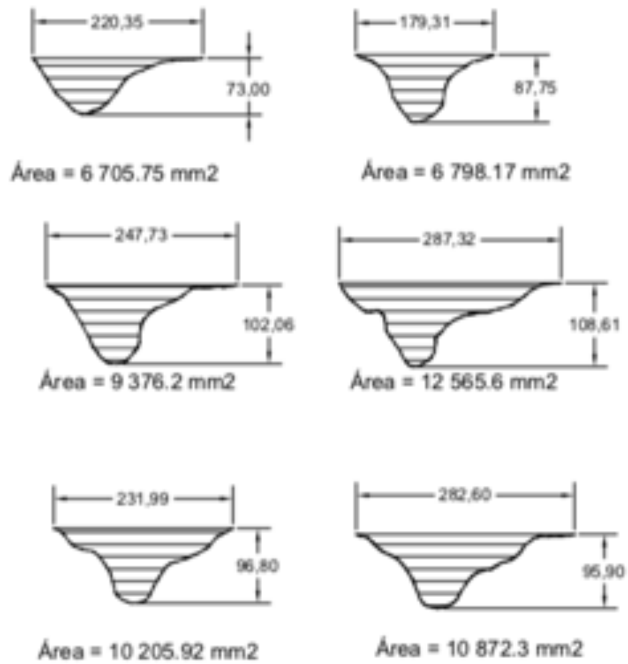


Figure 10. Slices of plaster 13.

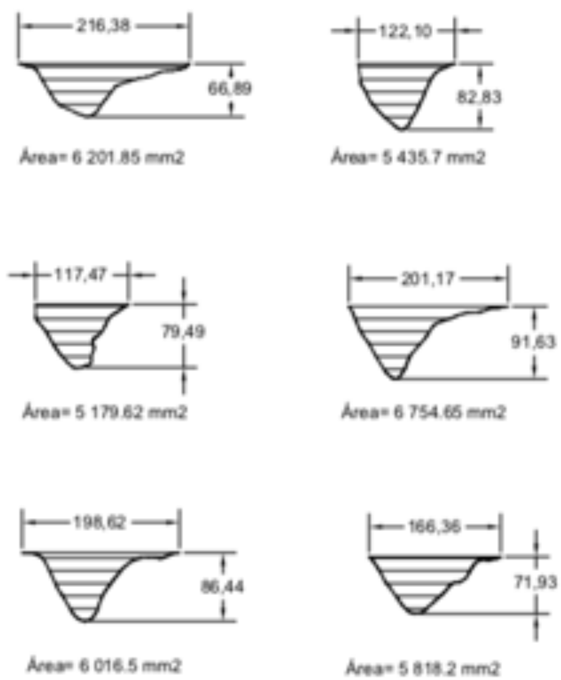


Figure 11. Slices of plaster 14.

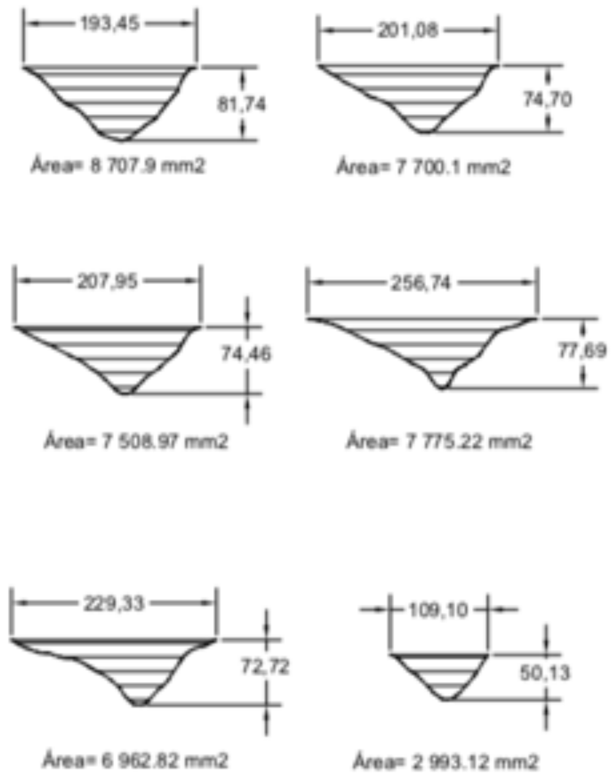


Figure 12. Slices of plaster 15.

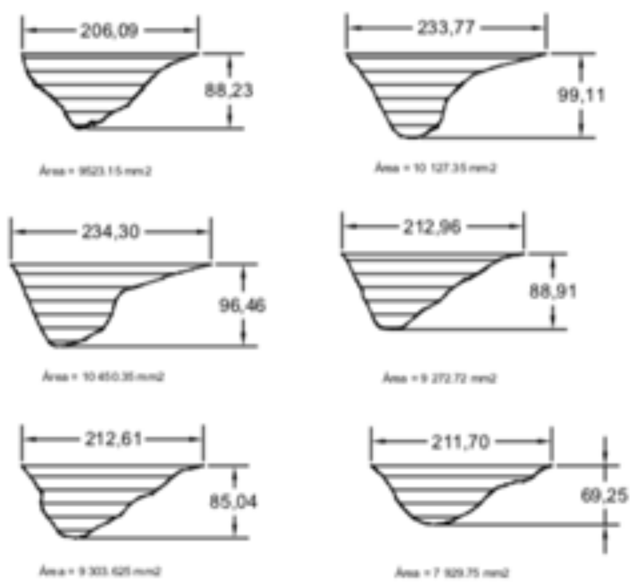


Figure 13. Slices of plaster 19.

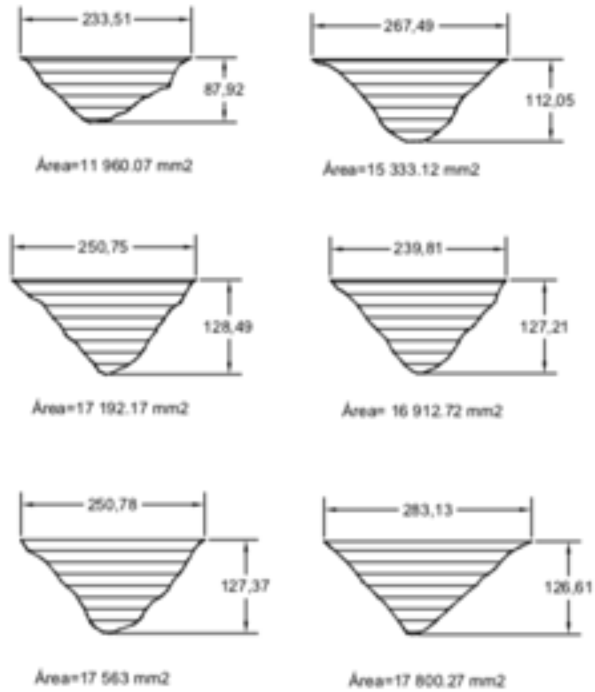


Figure 14. Slices of plaster 23.

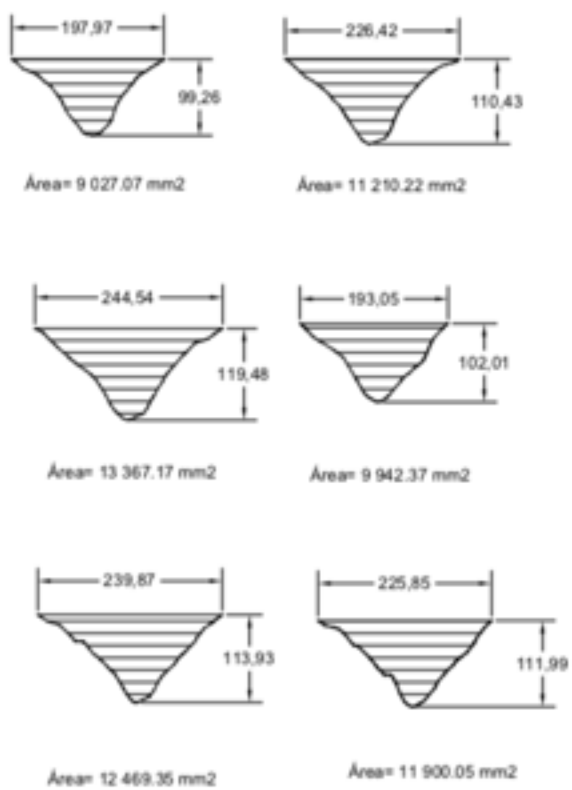


Figure 15. Slices of plaster 24.

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