Semiarid Terrain Alteration for Converting Dryland into Arable Land – Construction and Earthmoving Perspectives

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Abstract –

15% of world surface area is semiarid where 1.1 billion live, the most vulnerable people on earth. In contrast to arid, semiarid regions have substantial rainfall albeit it quickly evaporates and therefore vegetation and biomass growth is limited. A new concept calls for terrain alteration by earth moving to construct north-south slopes where on the northern slope in the northern hemisphere solar irradiation is reduced, causing in turn a reduction in evapotranspiration (ET), allowing for cultivation. The dimension of the slopes (or ridges) is on the order of 5-10 meter and its slope angle in the range of 15-20 degrees. This paper provides the motivation for such development and an overview of the necessary research and development for implementation. It also focuses specifically on the topic of earthmoving operations that are involved, the equipment it requires and discusses the potential for employing robotics and automated construction methods to improve the economic and environmental feasibility of such an endeavor.

Keywords –

Cultivation, earth moving equipment, food and agriculture, automatic and robotic construction.

1 Introduction

The world arable land in 2020 has been reduced to 44% of the arable land that was once available in 1960 (Figure 1). In the meanwhile, the world population has increased during this period by a factor of 2.63. This means that in 2020 each unit of arable land must produce 2.63/0.44 = 5.97 times more in comparison to a unit of land in 1960 and such an increasing productivity is hard to achieve. Subsequently, products like highly efficient fertilizers or weed killers have emerged, yielding gains in cultivation but impacting the environment. Therefore, to assure world food security more arable land is required. This could be achieved by creating a new "Green Revolution 2.0" for the semiarid world by the alteration of its terrain to enable a new extensive agriculture mode by retaining rainfall through reduction of ET. The artistic conception of earthmoving and construction of the slopes can be seen in Figure 2. As the proposed concept will be explained in the subsequent chapters, it imitates vegetation patterns that exist in nature. We hereby contribute an overview and a preliminary assessment from the construction and earthmoving point of view.

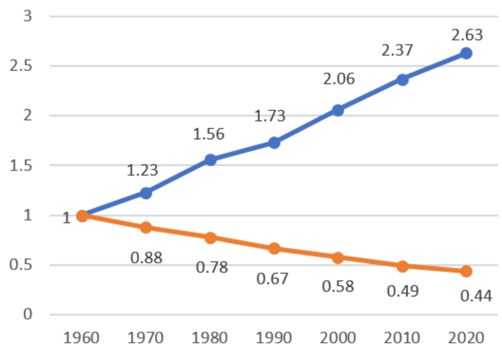

Figure 1. World population and arable land, 1960-2020 [1].

Figure 2. Artistic conception of earthmoving and construction of the North-South slopes.

2 Related work

Research on semiarid agriculture is limited in comparison to that of agriculture in temperate zones [2, 3]. Only a few industrialized countries have significant semiarid cultivation expertise such as in Australia, US Southwestern United States and Israel. There, semiarid land is used intensively in agriculture because large amounts of resources such as water, labor and fertilizer cannot be used per land unit. In contrast, however, most of the world's food is produced by extensive agriculture using large, accessible land areas where the output provides human food and animal feed.

As shown in Figure 3, the Northern slope in the northern hemisphere is lush, moist and green; the Southern slope is dry and unusable. Only the Northern slope is potentially cultivable. The proposed concept imitates vegetation patterns on natural north-south slopes.

Moreover, consider the following example (Figure 4): The annual precipitation in London, UK is 24 inches, while the annual precipitation in Dallas, TX is 35 inches. And yet London (51 degrees latitude) is green and lush while Dallas at 31.5° is semi-arid. A small difference in latitude and solar irradiation flux can cause a dramatic difference in vegetation and bio mass productivity.

Figure 3: Typical natural North-South slopes in semiarid areas.

Figure 4: Public Work, San Angelo, Texas. Grass appeared spontaneously on the Northern slope two weeks after creation

The concept outlined hereby is new and requires research and development on agronomic, plant and soil sciences, hydrology, climate and rainfall patterns, and atmospheric land interaction. Furthermore, the main variables for a return on investment analysis (ROI) are the cost to construct the slopes and the water "cost avoidance" by the water gain by rainfall retention. This paper explores the technologies that could be used to create and construct the slopes to provide cost-effective for new semiarid arable land that can be cultivated and yield results as shown in Figure 5.

Figure 4: Examples of cultivation on the Northern slope.

3 Man-made slopes

3.1 Slope design

The Northern and Southern slopes' widths are divided in a ratio of 2:1 or 3:1 in order to maximize the cultivable northern slope area (Figure 5). The Southern slope is steeper and therefore, to prevent soil erosion it will be covered by a plastic sheet. The sloping angle of the Northern slope will be determined by the "necessary" reduction of evapotranspiration required for different climates and crops intended for cultivation.

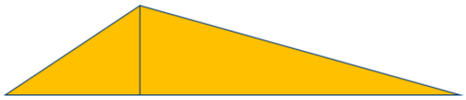

Figure 5: Cross-sectional view: Steep southern slope is covered with a plastic sheet to prevent soil erosion; the topsoil below the plastic sheet is scrubbed and placed on the northern slope.

The amount of earth moved by the construction of the slopes is proportional to the cross-section area of the slope triangles, which is proportional in turn to the square of the dimensions of the slope. To minimize the amount of earth moved and its associated cost, narrow slopes are preferable. But from the agronomic point of view wider slopes are more practical. In this effort we will determine the optimal dimensions to address these considerations.

The reduction of solar energy on the slope is expected to reduce evapotranspiration (ET). A shallow sloping angle will not produce enough reduction in solar input and reduction of ET. On the other hand, an overly steep angle will excessively reduce solar radiation and photosynthesis and also increase soil erosion and water runoff. An optimal altered ET will define the sloping angle for the "necessary" reduction of ET in comparison to that on flat terrain. The necessary ET will depend on local climate, growing seasons, and intended crops.

Any reduction of ET will decrease the difference between local precipitation and ET and the irrigation water requirement. The ideal case is when the new altered ET is less or equal to local precipitation. The altered new ET will determine the required sloping angle.

3.2 Relevant other factors

One concern is that the sloping terrain's soil will erode, requiring frequent correction and earthmoving. The steeper Southern slope, which is more susceptible to erosion, could be covered by a plastic sheet. As for the northern slope, we can learn from how hillsides are stabilized for crops such as grapes and winter wheat (Figure 6).

The topsoil on the Southern slope below the plastic sheet could be scrubbed and placed on the Northern slope. Also, if soil is eroded on the Northern slopes, it is not necessarily lost; it will accumulate in the areas between the slopes and if necessary, it could be spread back on the slope every few years.

Mathematical models of soil erosion and water runoff are difficult to create and run with acceptable accuracy, so these topics could be studied based upon the vegetation grown on natural slopes.

Danger to wildlife, birds and insects will be assessed and passage for desert animals will be created each few slopes to allow easy passage. An assessment of the impact on biotics will also be done by the agronomists and soil scientists taking part in this program.

Figure 6: Practiced hillside cultivation demonstrates how soil erosion and water runoff are prevented in the cultivation of natural slopes and can be implemented in the construction of man-made slopes.

4 Survey of potential sites

4.1 Geoinformation

Detecting differences between vegetation growth on natural sloping terrains with different inclination could be done using a spaceborne Synthetic Aperture Radar (SAR). Differences in vegetation between adjacent areas can be detected using SAR remote sensing techniques. This may be done for testing and demonstrating that indeed natural sloped terrains have different vegetation covers [4].

Spaceborne SAR has been used extensively to map and monitor vegetation since the 1990s, when the first SAR missions were launched. SAR sensors are active systems that transmit a coherent radar signal to the Earth's surface and measure the characteristics of the response backscattered from the target area. The interaction of the radar signal with vegetation is a function of the vegetation type and of the radar wavelength. Studies of forest biomass are typically carried out using longer wavelengths such as L-band as the signal is able to penetrate the canopy and interact with the branches and trunks of the forest [5]. Shorter wavelengths (e.g., X- and C-band) are less able to penetrate vegetation as they interact with leaves and smaller branches.

4.2 Relationship between topography and vegetation growth

Vegetation growth is affected by many factors such as soil moisture, air temperature, light, nutrients, soils, competition, predation, disturbance, species composition, and more. Variations in many of these variables are associated with attributes of local topography such as aspect, elevation, slope and inclination, as well as climate drivers. Topography strongly affects the distribution of insolation. Patterns of incoming solar radiation affect energy and water balances within a landscape, resulting in changes in air temperature, humidity and soil moisture, which in turn impact vegetation attributes.

In the Northern hemisphere, it is common sense that a southwestern slope is sunnier, hotter and drier than a northeastern slope because the apex of the sun is perpendicular to south-facing slopes. From the air, it is often easy to see the denser vegetation on north-facing slopes. However, in some parts of the world with plenty of moisture, vegetation may prefer south-facing slopes where they can thrive in the relative warmth.

Other factors such as climate, elevation, and species composition may further complicate these relationships. Jin et al. [6], for example, showed for the Qilian Mountain area of China that such aspects have a large impact on the vegetation at certain slopes and elevations due to changes in evapotranspiration. Figure 7 shows such a complex relationship between elevation, aspect, and Normalized Difference Vegetation Index (NDVI) based on remote sensing and elevation data. The NDVI is a dimensionless index that describes the difference between visible and near-infrared reflectance of vegetation cover and can be used to estimate the density of green on an area of land.

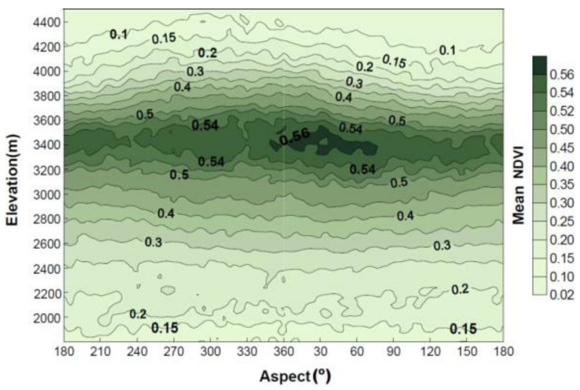

Figure 7: The change of the mean NDVI values with elevation and aspect in the northern part of Qilian Mountain. A Gaussian smooth filter was used and a low pass convolution was performed on the grid data to present a more consistent and smoother map. Note: a refiner scale (0.02) was used when the NDVI value is larger than 0.5 [6].

5 Construction of the slopes

The cost of earth moving cannot be compared to the cost of earthmoving done on relatively small areas such as for the foundations of buildings and road construction. In these operations earth is dug by bulldozers and excavators and is transported to certain distances by trucks.

In contrast, the proposed terrain alteration does not require actual moving of earth (Figure 8). The average level of the terrain remains the same as before the operation. It requires relatively shallow digging and landscape alteration without transporting earth. Despite this relatively localized work scope, the areal spread of the project makes earth moving a very important consideration. Furthermore, given the sustainability goals that are being targeted by the conversion of arid to semi-arid land, the earthmoving operations need appropriate planning to ensure that their cost and impact to environment are minimized in order to ensure the long-term economic and environmental feasibility of this project. Towards that end the following aspects are proposed for planning the earthmoving in this paper: (1) earthwork planning and analysis, (2) equipment selection, (3) construction and maintenance operations, (4) automation of operations, and (5) public perception. These topics are discussed in the following sections.

Figure 8: Earthmoving for north-south slopes construction.

5.1 Earthwork planning and analysis

The primary metrics of interest towards obtaining the cost estimate and schedule for the re-slope operations is determining the following metrics about earthwork: volume of earth to move, haul distances, and haul grades. These will inform the selection of equipment fleets and the total time and cost for project completion. Mass haul diagram will be employed for earthwork planning to obtain these measures.

- *Earthwork planning with mass haul calculations*: In order to convert a terrain of arbitrary topography to a sloped terrain, the contractor determine the amount of earth to be moved and the distance over which such movement occurs. This requires capturing the Digital Terrain Model (DTM) of the area, preferably using an arial lidar survey; and overlaying it with the proposed sloped terrain to identify where the cut and fill sections of the project would be. For purposes of planning, the entire area would be subdivided into a suitable grid (e.g., 5x5 meters). The difference between existing and planned terrain will provide an identification of cut and fill grid sections, cut and fill elevation differences, and volume to be moved between grid sections. These factors will inform the choice of equipment to be employed.
- *Contract administration:* The contract for the earthwork will expect to be paid on a unit-cost basis per unit volume of soil. The exact amount of the unit cost will be determined based on existing project site conditions.
- *Operation time:* Because the work is expected to be conducted in a semi-arid location, the most effective time for performing the primary earthwork tasks would be during or (preferably) just after the wet season. This is because the rainwater that has permeated the soil can help improve the plasticity of soil, and thereby ease the workload on the earthwork equipment.

5.2 Equipment selection and development

The primary earthwork tasks that are expected to be performed are earthmoving, ploughing, grading to the desired slopes. Given that these projects will mostly occur in relatively non-undulating terrain, it is expected that there will be little need for moving earth across grid sections. Thus the primary equipment needs will be for ploughing the soil for mixture of nutrients and grading.

- *Soil Grading:* Thus, the primary equipment for shaping the terrain into slopes is expected to be motor-graders after the soil has been sufficiently ploughed and infused with nutrients. Typical motor grader widths range from
- *Ploughing the soil:* The task of deep-ploughing (up to 2 m depth) could be done with rippers attached to dozers, while shallow plowing (up to 0.3 m depth) and mixing could be done with the scarifier implement attached to the motor-grader. Given that it is expected to require ploughing to greater depths, custom-built ploughs and implements that attach on to the grader or a dozer could be considered.
- *Soil Stabilization:* It may be required to perform methods to stabilize the soil to maintain the slopes. This will be done by mechanical means, rather than chemical due to the need to grow crops on the slopes.

Given the unique nature of the project, there is quite a considerable potential for the development of novel equipment: for example size and scalability are expected that this project can necessitate the development of novel implements for deep ploughing, nutrient mixing, and large-width grading.

5.3 Construction and maintenance of slopes

The primary construction of slopes will be performed using motor graders that are equipped with APG-enabled automated machine guidance and control (AMG and AMC). This technology uses real-time data from GPS sensors of receivers attached to the graders moldboard to automatically adjust the angle and pitch of the moldboard to obtain the desired shape of slope in the given terrain. This technology augmented the operator’s capabilities and ensures adheres to plans that are uploaded to the motor graders AMG system.

Apart from the initial construction of the slopes, annual maintenance may be required to offset any soil erosion caused by wind or other forced. It is expected that for a slight grading a single grader will suffice for an entire area (e.g., 10 square kilometers). Agricultural operations related to sowing and harvesting can be performed using conventional agricultural equipment.

5.4 Automation of operations

Since the majority of earth moving contractors already have difficulty finding skilled equipment operators or turn down work, it is posited that a project of such large scope and relatively simplistic operations in remote locations provides the ideal testing and proving grounds for the automated construction equipment and their operations. Apart from the previously mentioned automation methods such as AMG and AMC for grader control that will be heavily used in this project, these operations will also enable the testing of autonomous graders and soil stabilizers.

Such automated operations could use robotic graders (such as are used for road leveling or snow plowing). Robots can solve the problem because automatic steering of vehicles in this use case does not require to frequently turn, stop or drive in reverse; they can cruise relatively fast in straight lines making rapid inexpensive terrain alteration and do this automatically in repetitive cycles of typical operations. This eliminates waste like it is common in general construction projects (e.g., schedule and cost overruns, over-allocation of resources, not optimal maintenance tasks). Likewise, high demand is set on a variety of technology that needs to safely steer the vehicles in rough(er than expected) terrain. Safety in equipment operation as it relates to detecting pedestrians, animals, or other obstruction close or nearby to it, s always a concern and specifically when it comes from the exploration or use of driverless machines [8]. There are numerous other challenges in the automation of earth-moving machines [9, 10]

5.5 Public perception of operations

Given the large-scale nature of operations involved in natural terrain, it will be necessary to clearly communicate the cost and benefits of this project to the public. Metrics such as construction duration and costs, emissions produced, along with the fruits of the project such as crops grown must be clearly understandable to the public. Towards this end, novel tangible user interfaces of Augmented Reality (AR) sandboxes to plan the project and visualize the metrics of interest on the project in response to user input [11].

Previous experiences and works in developing earthwork calculation applications for the AR sandbox for highway construction (Figure 9) and traffic analysis purposes can inform non-literate bystanders of the development. For example, novel visualizations and tangible interactive planning tools will result for the project. These can serve as a public interaction and dissemination tool to engage with the public and improve their perception about this project while sensors on unmanned aerial vehicles (UAVs) provide run-time project state data [12] that can be used in digital terrain modeling or earthwork planning [13-14].

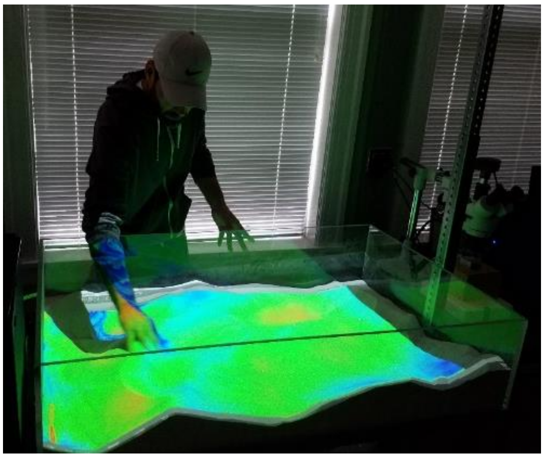

Figure 9: Interactive terrain visualization using a AR sandbox.

6 Conclusion

15% of the world surface area is semi-arid where 1.1 billion people live. In the Northern hemisphere the North-South slopes have the potential to produce jobs, to promote economic development and to provide food security for developing countries. In some cases, agribusiness corporations are likely to invest, buy land, upgrade and cultivate it for export.

The presented work is a preliminary study on revitalizing the concept of North-South slopes for the application of converting dryland into arable land. Explanations to the design and construction methods were presented as they relate to the topic of automatizing and robotizing earth movement equipment in construction. A variety of topics like the impact on converting naturally-built states in the environment and the potential impact on climate and food supply where touched upon but deserve much more attention in future studies.

References

[1] Higgins, G.M. and Kassam, A.H. (1981). "The FAO agro-ecological zone approach to determination of land potential." *Pedologie*, *31*, 147–168.

[2] Scholes, R.J. (2020). "The Future of Semi-Arid Regions: A Weak Fabric Unravels." *Climate*, Vol. 8(3), 43, https://doi.org/10.3390/cli8030043.

[3] Ricart, S., Villar-Navascués, R.A., Hernández-Hernández, M., Rico-Amorós, A.M., Olcina-Cantos, J., Moltó-Mantero, E. (2021). "Extending Natural Limits to Address Water Scarcity? The Role of Non-Conventional Water Fluxes in Climate Change Adaptation Capacity: A Review." *Sustainability*, 13(5), 2473, https://doi.org/10.3390/su13052473.

[4] Desta, F., Colbert, J.J., Rentch, J.S. Gottschalk, K.W. (2004). "Aspect induced differences in vegetation, soil, and microclimatic characteristics of an Appalchian watershed." *Castanea*, 69(2): 92-108.

[5] Beaudoin, A., Le Toan, T., Goze, S., Nezry, E., Lopes, A., Mougin, E., Hsu, C.C., Han, H.C., Kong, A., Shin, T. (1994). "Retrieval of forest biomass from SAR data." *International Journal of Remote Sensing*, 15(14), 1994, https://doi.org/10.1080/01431169408954284.

[6] Jin, X.M., Zhang, Y.K., Schaepman, M.E., Clevers, J.G.P.W., Su, Z. (2008). "Impact of elevation and aspect on the spatial distribution of vegetation in the Qilian mountain area with remote sensing data." The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences (ISPRS), 1385-1390.

[7] Rabus, B., Eineder, M., Roth, A., Bamler, R. (2003). "The shuttle radar topography mission - a new class of digital elevation models acquired by spaceborne radar." *ISPRS Journal of Photogrammetry and Remote Sensing*, 57(4), 241-262,

https://doi.org/10.1016/S0924-2716(02)00124-7.

[8] Golovina, O., Teizer, J., Johansen, K.W., König, M. (2021). "Towards Autonomous Cloud-based Close Call Data Management for Construction Equipment Safety." Automation in Construction, 132, 103962, https://doi.org/10.1016/j.autcon.2021.103962.

[9] S. Dadhich, S., Bodin, U., Sandin, F., Andersson, U. (2018). "From tele-remote operation to semi-automated wheel-loader." *Int. J. Electr. Electron. Eng. Telecommun.,* 7(4), 178–182, doi: 10.18178/ijeetc.7.4.

[10] Dadhich, S., Bodin, U., Andersson, U. (2016). "Key challenges in automation of Earth-moving machines." *Automation in Construction*, 68, 212–222, https://doi.org/10.1016/j.autcon.2016.05.009.

[11] Joseph Louis, J., and Lather, J. (2020). "Augmented Reality Sandboxes for Civil and Construction Engineering Education." Proceedings of the 30th International Symposium on Automation and Robotics in Construction, 750-756, https://doi.org/10.22260/ISARC2020/0104.

[12] Siebert, S., Teizer, J. (2013). „Mobile 3D mapping for surveying earthwork using an unmanned aerial vehicle (UAV)." Proceedings of the 30th International Symposium on Automation and Robotics in Construction, Montreal, Canada, August 11-15, 2013, https://doi.org/10.22260/ISARC2013/0154.

[13] Teizer, J., Green, A., Hilfert, T., Perschewski, M., König, M. (2017). "Mobile Point Cloud Assessment for Trench Safety Audits." 34th International Symposium on Automation and Robotics in Construction, Taipei, Taiwan, https://doi.org/10.22260/ISARC2017/0021.

[14] Teizer, J. (2007). "Rapid Surveillance of Trenches for Safety." Proceedings of the Construction Research Congress, Freeport, Bahamas, May 6-8, 2007.