REFEREED PAPER

IMPACT OF SOIL AND WATER CONSERVATION STRUCTURES ON STREAM FLOW REDUCTION IN THE SUGAR INDUSTRY OF SOUTH AFRICA

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Abstract

Soil conservation seeks to avoid and moderate soil loss through erosion and to also promote the increased infiltration of rainfall into the soil, thereby slowing down and reducing the amount of runoff. In South Africa, contour banks and spill-over roads are the soil and water conservation structures that are generally employed for the protection of cropland against erosion in the sugar industry. Stream Flow Reduction (SFR) is the decrease in runoff as a consequence of anthropogenic activities and it is influenced by the distribution and infiltration properties of soils, the distribution of vegetation types, as well as the topography and climate. For an activity to be considered for declaration as an SFR activity in South Africa, its impact on SFR should be significant (i.e. an impact ≥ 10% of Mean Annual Runoff). The objective of this study is to investigate the impact of soil and water conservation structures on SFR in the sugar industry of South Africa. The study area consists of sugarcane-growing areas in South Africa. The results of model simulations showed that soil and water conservation structures result in SFR across all soil types and practices in the sugar industry. This was due to the fact that soil and water conservation structures intercept runoff and increase the amount of water infiltrating into the soil, thereby slowing down and reducing the amount of runoff. However, the SFR caused by soil and water conservation structures is insignificant (i.e. < 5.5%) and would not necessitate their declaration as SFR activities, as contained in the National Water Act of South Africa.

Keywords: Soil and water conservation, South Africa, stream flow reduction, sugarcane

Introduction

Plant growth, agricultural yields and water quality are adversely hindered by soil erosion (Issaka and Ashraf, 2017). Poor land management, which causes damage to soil and leads to water runoff across a landscape, instead of adequate infiltration, is one of the factors that causes erosion (Liu, 2016). Soil conservation is the avoidance or moderation of soil that is lost through erosion (Sustainet, 2010). The purpose of soil conservation is to maintain the rate of soil loss at levels that are lower than the soil formation rate (Morgan, 2005). In addition, soil conservation increases the amount of water infiltrating into the soil, which slows down and reduces the amount of water running off (Sustainet, 2010). Many soil conservation practices exist, ranging from mechanical structures (e.g. contour bunds, terraces and check dams) to soil management practices and agronomic measures (e.g. cover crops, tillage, mulching, vegetation strips, re-vegetation and agroforestry) (Krois and Schulte, 2014). Generally, crop cover and management practices reduce runoff to a greater extent than soil and water conservation structures (Maher, 1990). Extreme rainfall events do not necessarily translate into extreme runoff events, as variations of crop cover, at different stages of sugarcane growth, play a major role in the runoff volume that is generated (Otim *et al.*, 2020a). Maintaining crop cover over a soil surface significantly reduces the runoff. Nonetheless, conservation structures are necessary to reduce both runoff and erosion after the crop cover has been removed. The management of land cover impacts runoff in various ways (USDA-ARS, 2013). For example, tillage practices, which mechanically disturb the soil surface, reduce runoff on soils with no biomass, compared to soils that have been left undisturbed for several years. Tillage-induced roughness has a significant impact on runoff and erosion (Takken *et al.*, 2001) and the rougher the soil surface, the greater the infiltration, thereby reducing the runoff and erosion from the surface (Lavee *et al.*, 1995; Battany and Grismer, 2000). According to SASA (2002), waterways, contour banks and spill-over roads are soil and water conservation structures that are employed to protect cropland against erosion in South African sugar industry. Contour banks are constructed across a slope, in order to intercept runoff water (Matthee and van Schalkwyk, 1984) and safely discharge it into stable grassed waterways or natural drains (Carey *et al.*, 2015). Spill-over roads, on the other hand, allow runoff to flow from a higher field across the road structure to a lower field (SASA, 2002). Besides the positive effect of soil and water conservation measures on the hydrology, they increase infiltration and lower the runoff, thereby leading to a lower soil loss rate (Nyssen *et al.*, 2009). Generally, the catchment runoff response from rainfall events depends on the interaction between the rainfall amount and its intensity, the antecedent soil moisture conditions and land cover (Maher, 2000). In addition, the runoff coefficients increase with the decreasing soil water storage capacity, soil depth and soil cover during rainfall events (Valentin *et al.*, 2008).

In South Africa, soil and water conservation practices are governed by the Conservation of Agricultural Resources Act (CARA) 43 of 1983, which states that, “The objectives of this Act are to provide for the conservation of the natural agricultural resources of the Republic by the maintenance of the production potential of land, by the combating and prevention of erosion and weakening or destruction of the water sources, and by the protection of the vegetation and the combating of weeds and invader plants” (CARA, 1983).

Article 6 on “Control measures”, gives guidance to land users on soil and water conservation practices in South Africa, as illustrated below:

(a) the utilization and protection of land that is cultivated;
(b) the prevention or control of waterlogging or the salination of land;
(c) the regulating of the flow pattern of runoff water;
(d) the restoration or reclamation of eroded land, or land which is otherwise disturbed or denuded;
(e) the protection of water sources against pollution on account of farming practices; and
(f) the construction, maintenance, alteration or removal of soil conservation works, or other structures, on land.

Stream flow comprises the runoff from the catchment under consideration and the runoff contribution from all upstream catchments (Schulze *et al.*, 1995). On the other hand, Stream Flow Reduction (SFR) is the decrease in various aspects of the overall flow regime (Smakhtin, 2001). Therefore, a reduction in runoff is synonymous with an SFR. According to the NWA (1998), commercial forestry is the only current Stream Flow Reduction Activity (SFRA) that has been declared in South Africa, but any activity including the cultivation of any particular crop may be declared as a SFRA if that activity is likely to reduce the availability of water in a water course. Intensive agriculture systems (e.g. semi-permanent and permanent cash cropping, and monoculture plantations) are associated with negative impacts, like changes in the stream flow response and increased surface erosion (Ziegler *et al.*, 2009). According to Bruijnzeel (2004), the net impact on the amount and timing of stream discharge that is associated with forest conversion to agriculture is a combination of evapotranspiration and soil infiltration. The impact of sugarcane on the water resources is likely to be negligible in both the North Coast and South Coast, whereas it is possible that sugarcane has a significant impact on the available water resources in the Midlands (Jewitt *et al.*, 2009). Therefore, consideration should be given to the regulation of sugarcane as an SFRA. For an activity to be considered for declaration as an SFRA, its impact should be significant (i.e. impact ≥ 10% of the Mean Annual Runoff (MAR)) and the geographic extent should also be significant (i.e. area ≥ 10% of the quaternary catchment under consideration) (Jewitt *et al.*, 2009). Factors that influence SFR include the spatial distribution and the infiltration properties of soils, the hydraulic characteristics and extent of aquifers, the rate, frequency and amount of recharge, the evapotranspiration rates, the distribution of vegetation types, as well as the topography and climate (Smakhtin, 2001). In general, the major processes that control evapotranspiration include rainfall interception, net radiation, advection, turbulent transport, leaf area and the plant-available water capacity (Zhang *et al.*, 1999). Rainfall is the most dominant factor that initiates, drives and sustains runoff (Schulze *et al.*, 1995). The quantification of SFR involves a comparison of the stream flows associated with a given activity, against the baseline stream flows (Jewitt *et al.*, 2009). Hence, the objective of this paper was to investigate the impact of soil and water conservation structures on stream flow reduction in the sugar industry of South Africa. It is important to note that the stream flow reduction of growing sugarcane, compared to natural vegetation, will not be considered.

Methods and Assumptions

This investigation follows a previous study by Otim *et al.* (2020b), in which the runoff volume, peak discharge and sediment yield were simulated with the Agricultural Catchments Research Unit (*ACRU*) model and verified against the observed data from bare fallow and sugarcane fields. Based on the results, Otim *et al.* (2020b) concluded that the *ACRU* model is suitable for the simulation of the runoff volume, peak discharge and sediment yield from catchments under both bare fallow and sugarcane land cover in South Africa. Subsequently, this investigation utilised the data and results of runoff simulated with the *ACRU* model from a hypothetical 1 km^2 catchment for the four homogenous climatic zones (i.e. the Midlands, South Coast, North Coast and Zululand and Irrigated) in the sugar industry of South Africa. The study area, methodology and assumptions are presented in Otim (2020). The mean annual rainfall for the South Coast, North Coast, Zululand and Irrigated and the Midlands regions are 934, 1 146, 642 and 818 mm, respectively, while the respective ratoon lengths are 16, 13, 12 and 21 months. In addition, the sugarcane replant cycles after the last ratoon crop are 10, 10, 7 and 16 years for the South Coast, North Coast, Zululand and Irrigated and Midlands regions, respectively. Over 46 080 scenarios were simulated for the period 1950-2017 (i.e. 68 years), as shown in Otim (2020), but for the purposes of this study, only a few select scenarios were used in the analysis of the various scenarios. This is because the volume of the simulated runoff in a given region, and for a given soil and water conservation practice, remained the same.

In order to assess the impact of the soil and water conservation structures on Stream Flow Reductions (SFRs), the simulated scenarios were summarised into two broad scenarios. For Scenario 1, it was assumed that the sugarcane was grown on fields without soil and water conservation structures (i.e. baseline activity) and for Scenario 2, the sugarcane was grown on fields containing soil and water conservation structures. The SFRs were estimated by subtracting the annual average flows of Scenario 1 from Scenario 2 and a negative value denotes an SFR that is significant, if its impact is ≥ 10% of the MAR. On the other hand, a positive value would denote an increase in stream flow. The resultant simulated SFRs were plotted and analysed for each soil and water conservation practice, for the various soil textural classes and for each homogenous climatic zone in the sugar industry. In addition, the SFRs for all the homogenous climatic zones were plotted in a single graph to assess how the regions compare to each other.

Results and Discussion

The results, analysis and discussion of the impact of soil and water conservation structures on SFRs, across the different homogenous regions, are presented below:

Impact of soil and water conservation structures on stream flow reduction

Plots of the SFRs against each soil and water conservation practice for the various soil textural classes for the North Coast, in the sugar industry of South Africa, are shown in Figure 1. The SFR varies between 0.02% and 0.80% of the MAR from fields without soil and water conservation structures (i.e. baseline activity) in the North Coast, with a higher SFR in the clayey soils than in the sandier soils, as shown in Figure 1. The relationship that is exhibited is logical, because clayey soils have a higher water-holding capacity and can store more rain water, which results in a lower infiltration rate and less runoff, compared to sandier soils. The SFRs for the South Coast, Midlands and Zululand and Irrigated regions are summarised in Table 1.

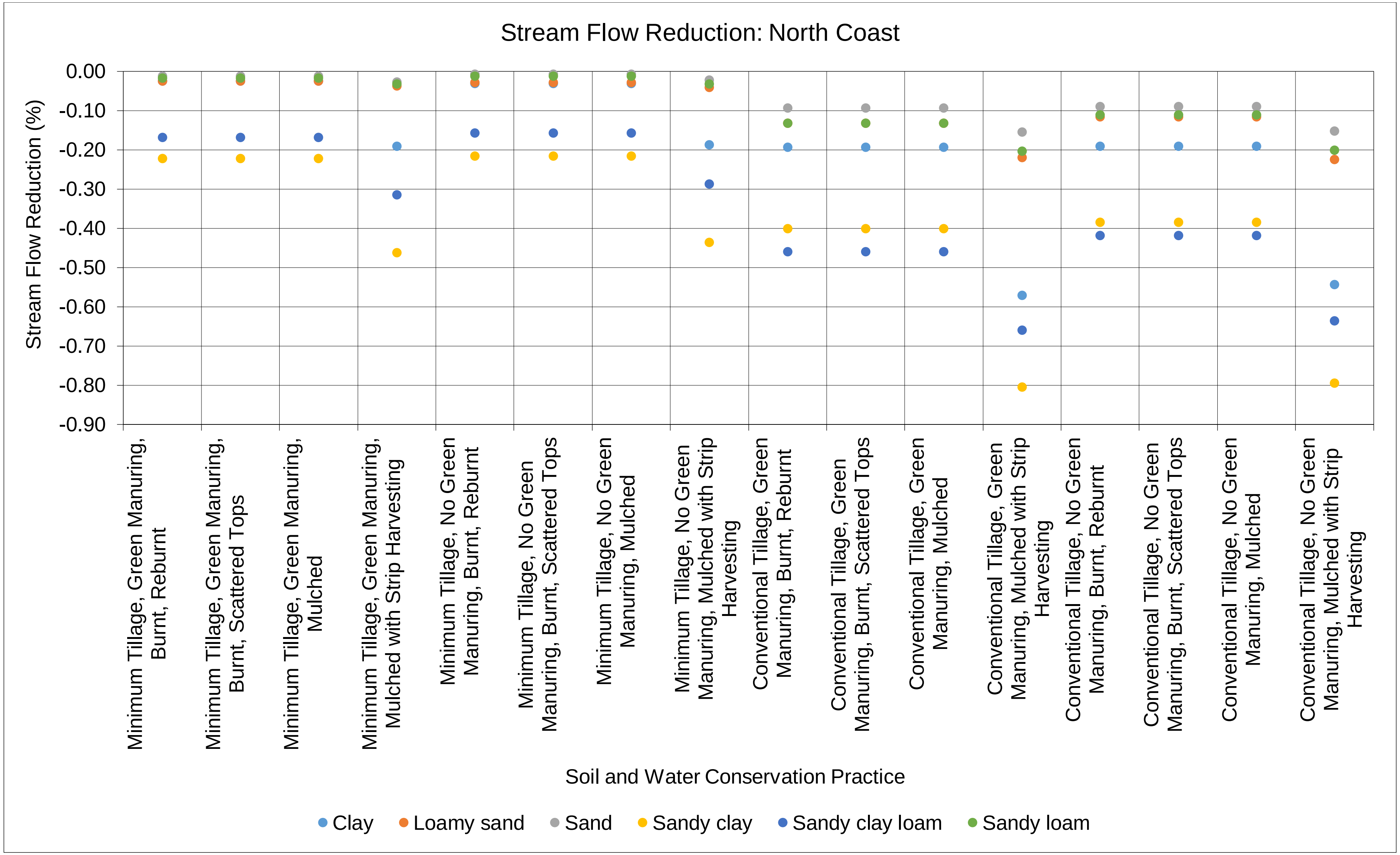

Figure 1. SFRs due to soil and water conservation structures in sugarcane fields in the North Coast region

Table 1. Variation of SFRs as a percentage of MAR from baseline activities in the South Coast, Midlands, and the Zululand and Irrigated regions

Region	SFR (%)
South Coast	0.00 – 0.42
Midlands	0.05 – 1.91
Zululand and Irrigated	0.28 – 5.36

The SFRs for the South Coast, Midlands, and Zululand and Irrigated regions also follow similar relationships to the SFRs in the North Coast, and the plots are shown in Figure 2 to Figure 4.

Based on the above observations, it is evident that soil and water conservation structures cause decreases in the stream flow (i.e. negative values) across all regions, soil types and practices. This is consistent with the observations of Nyssen *et al.* (2009), who noted that soil and water conservation structures intercept runoff and increase the amount of water infiltrating into the soil, thereby slowing down and reducing the amount of water running off. The combination of soil and water conservation structures and agronomic practices, such as strip harvesting and conventional tillage, yielded the greatest reduction in SFR. This is because strip harvesting ensures that significant portions of soils are covered, thereby intercepting water drops and decreasing the kinetic energy of rain drops. This, in turn, increases the time necessary for infiltration, hence reducing the runoff, which is consistent with the observations made by the USDA-ARS (2013). In addition, conventional tillage practices mechanically disturb the soil surface, causing roughness, which increases infiltration and reduces runoff, which is in agreement with Takken *et al.* (2001).

According to Jewitt *et al.* (2009), activities with an impact of greater than or equal to 10% of the MAR on SFR should be considered for declaration as SFRAs. Therefore, the impact of soil and water conservation structures on SFR is insignificant (i.e. < 5.5%) and does not necessitate declaring the soil and water conservation structures in sugarcane production as SFRAs, as contained in the National Water Act of South Africa. In addition, soil and water conservation structures regulate the flow pattern of runoff and combat erosion, which is a requirement of the Conservation of Agricultural Resources Act (CARA) 43 of 1983. Therefore, eliminating soil and water conservation structures would decrease SFR, but it would increase soil erosion, which is undesirable, and it would also reduce the water quality in streams.

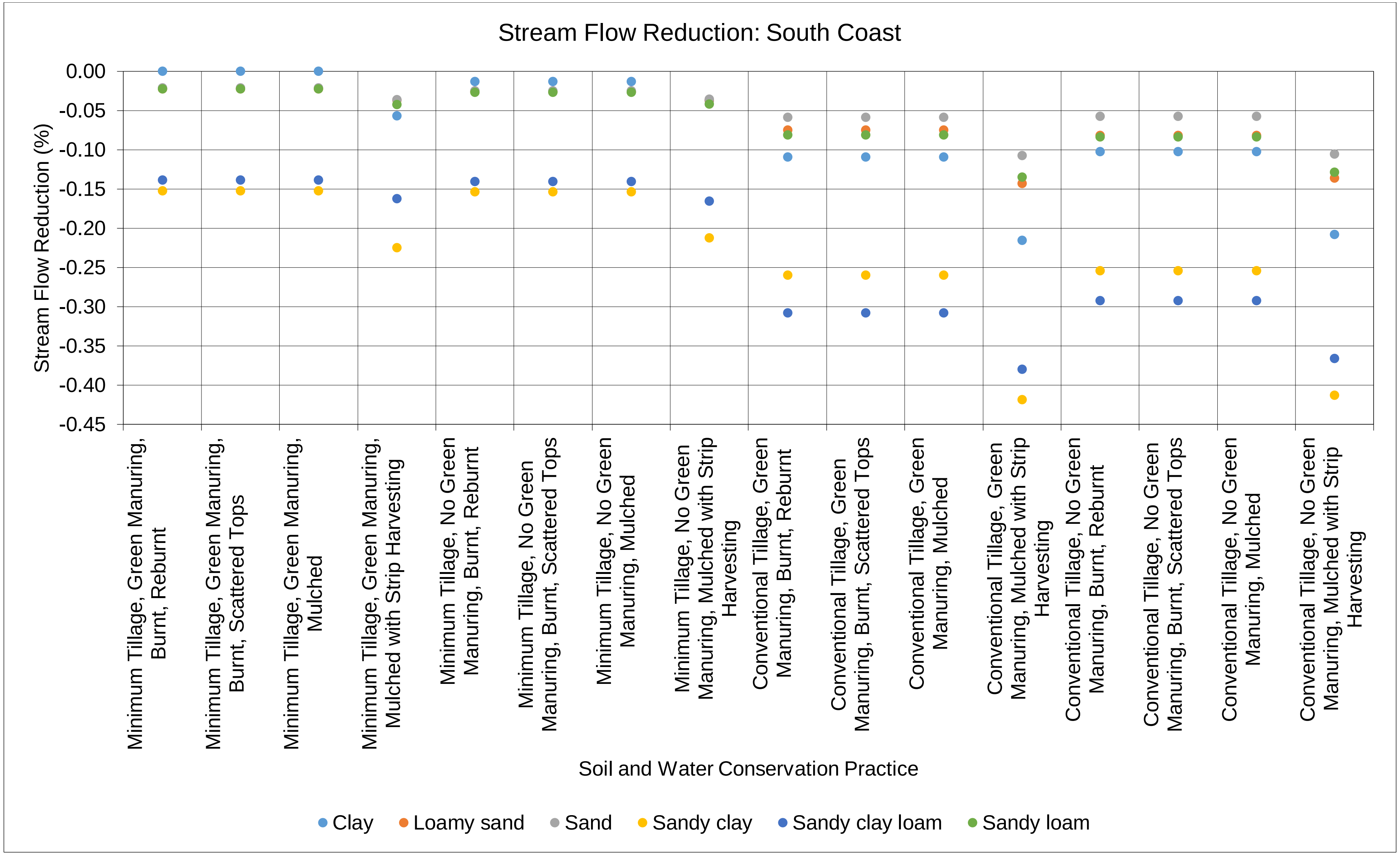

Figure 2. SFRs due to soil and water conservation structures in sugarcane fields in the South Coast region

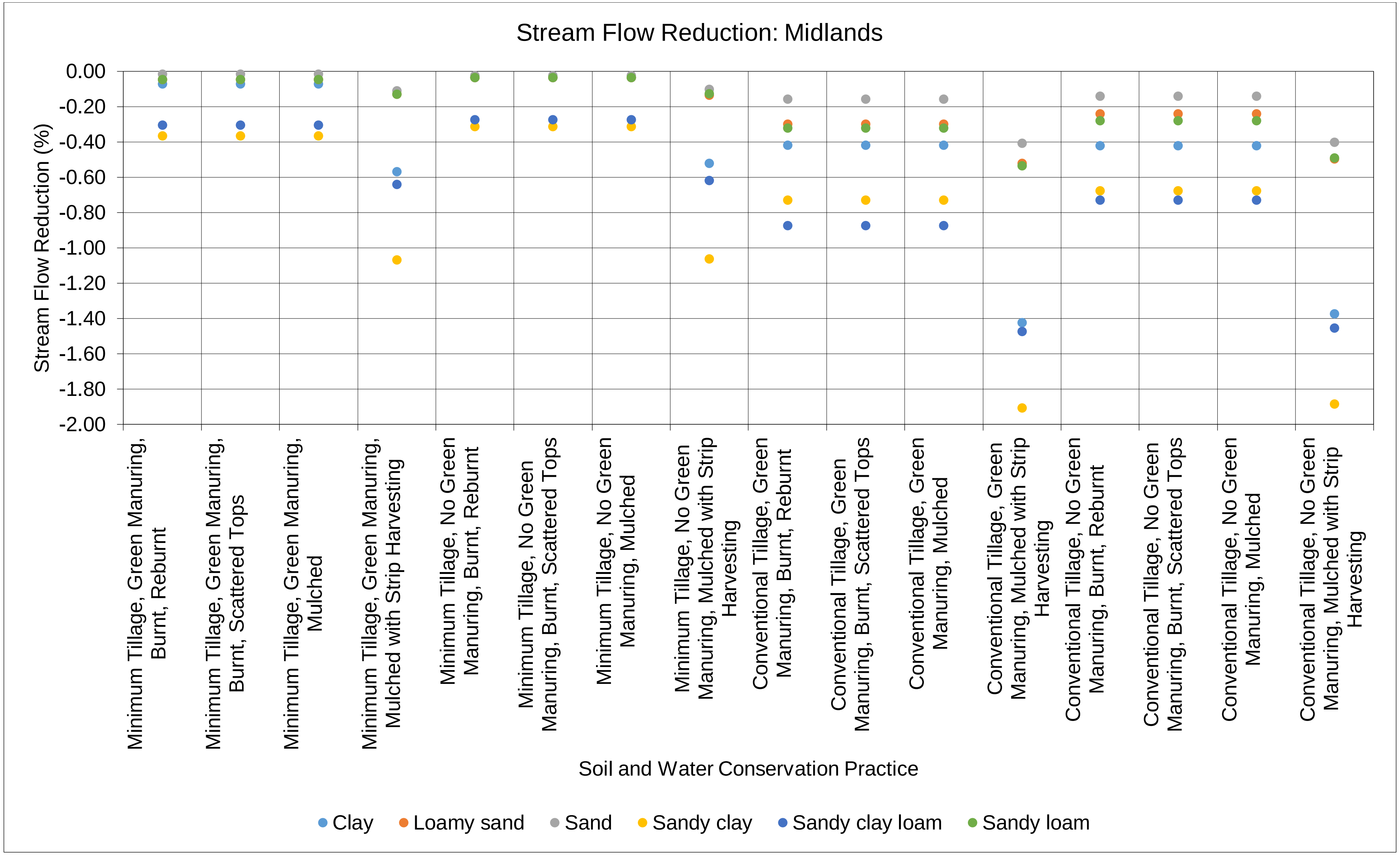

Figure 3. SFRs due to soil and water conservation structures in sugarcane fields in the Midlands region

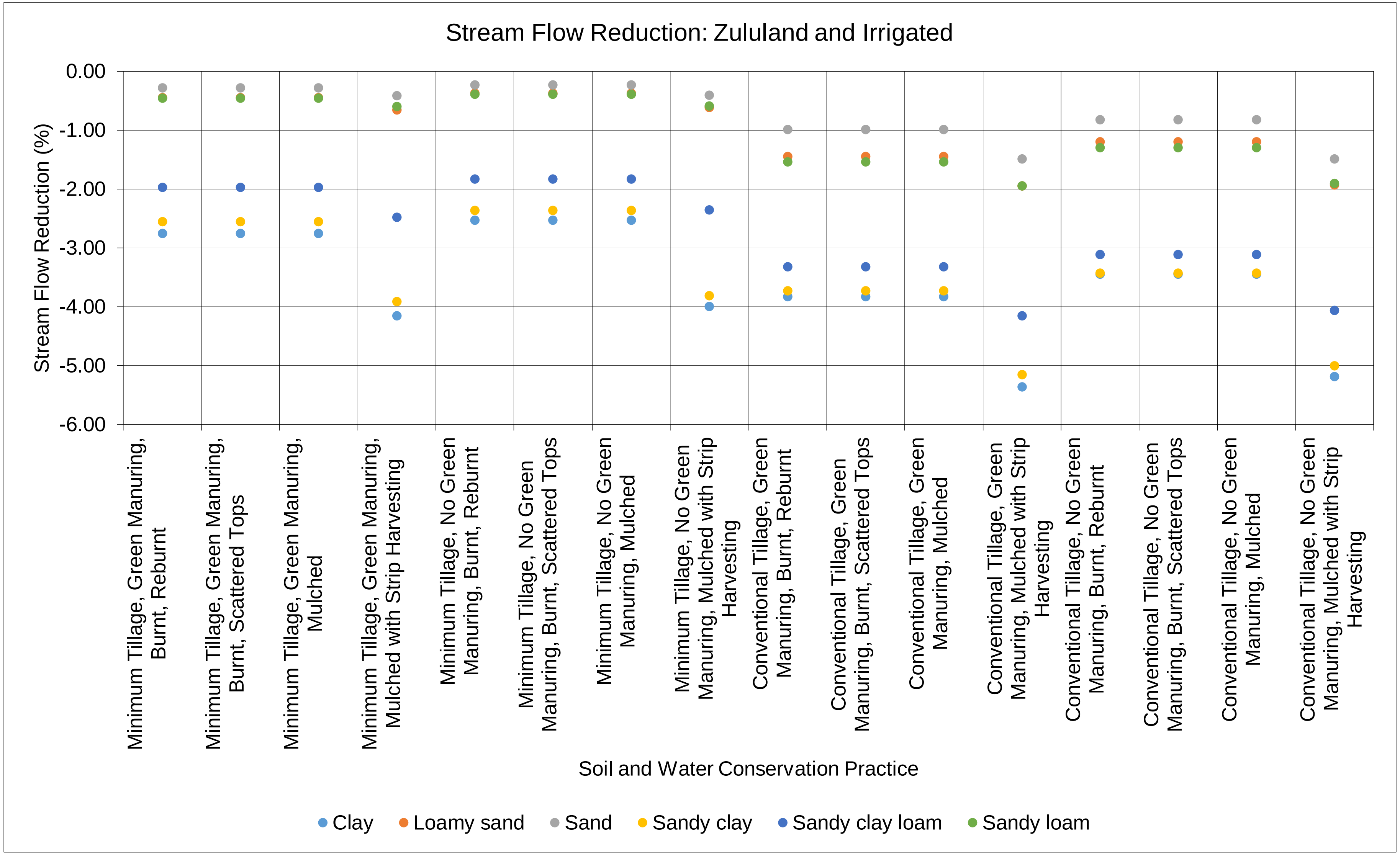

Figure 4. SFRs due to soil and water conservation structures in sugarcane fields in the Zululand and Irrigated region

Relationships in the stream flow reduction due to soil and water conservation structures across different homogenous climatic zones

Graphs depicting the relationships in SFRs, due to soil and water conservation structures in sugarcane fields in the various homogenous regions, are shown in Figure 5. The greatest SFR occurs in the Zululand and Irrigated region, followed by the Midlands, North Coast and South Coast regions. The different magnitudes of the SFRs in the regions are attributed to variations in the climate, the ratoon length and sugarcane replant cycles in the homogenous regions. The high SFR in the Zululand and Irrigated and Midlands regions, which receive 642 and 818 mm of rainfall, respectively, is because of the lower rainfall received and the fact that most of the rainfall received coincided with the periods of high crop cover, hence less runoff was generated and more SFR. On the other hand, the low SFR in the South Coast and North Coast regions, which receive 934 and 1 146 mm of rainfall, respectively, is because more rainfall was received and the fact that most of the rainfall received coincided with periods of low crop cover, thus generating more runoff and less SFR. These observations are consistent with those of Schulze *et al.* (1995) who noted that rainfall is the most dominant factor that initiates, drives and sustains runoff. Otim *et al.* (2020a) concluded that variations of crop cover at different stages of sugarcane growth play a major role in the runoff volume that is generated and that maintaining the crop cover over the soil surface significantly reduces runoff. However, the differences in the magnitude of SFR are insignificant, because they are all less than 10% of the MAR. The relationships exhibited are similar in trend, irrespective of the soil textural class, with the only differences occurring in the magnitudes of the SFR.

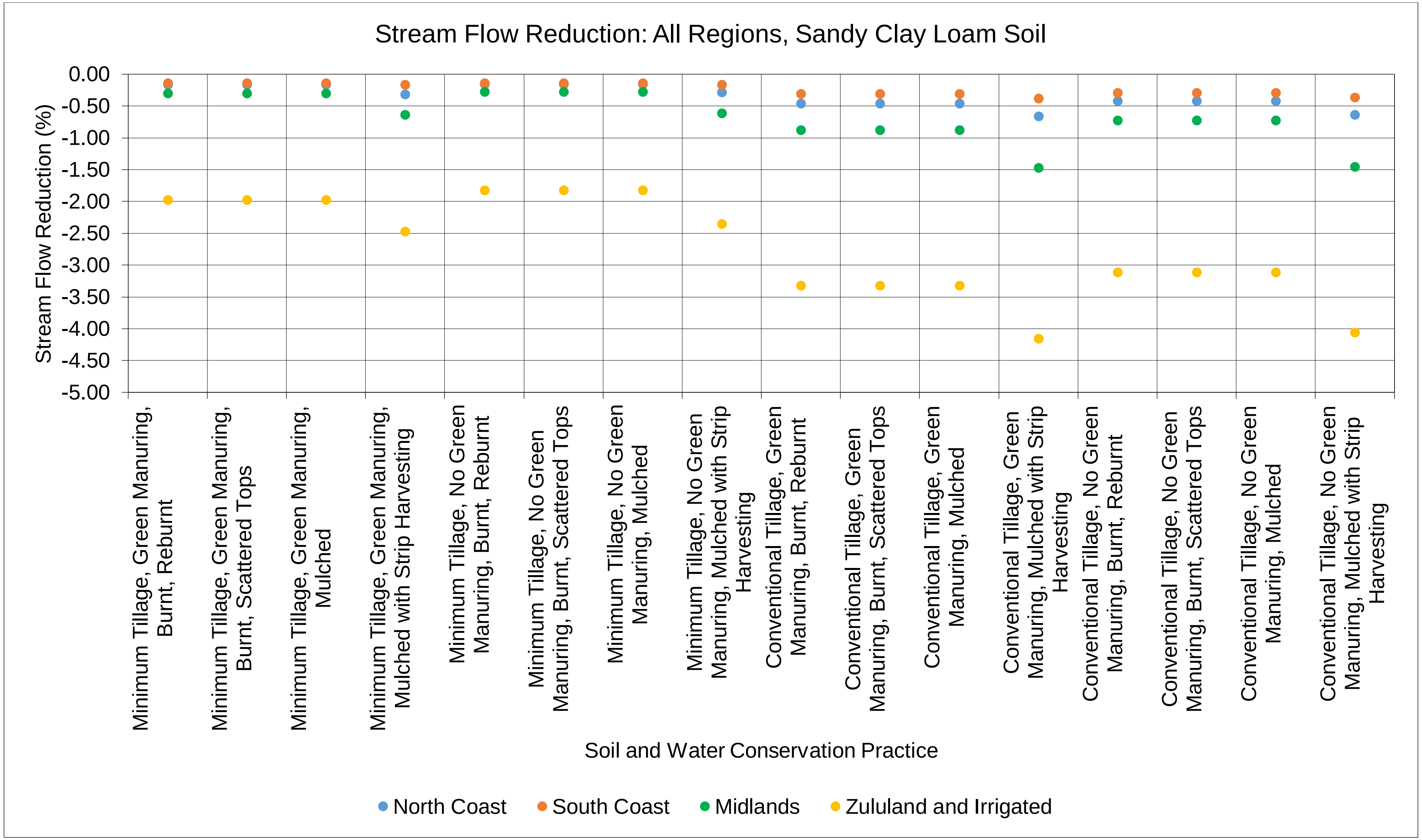

Figure 5. Relationship of SFRs, due to soil and water conservation structures, in sugarcane fields in the various homogenous regions

Conclusions

Generally, the impact of soil and water conservation on SFRs varies between 0.02% and 0.80% in the North Coast region, while in the South Coast, Midlands and Zululand and Irrigated regions, it varies between 0.00% and 0.42%, 0.05% and 1.91% and 0.28% and 5.36%, respectively. The SFR is greater in clayey soils than in sandier soils, because clayey soils have a higher water-holding capacity and can store more rain water, resulting in a lower infiltration rate and less runoff, compared to sandier soils. Furthermore, the greatest SFR occurs in the Zululand and Irrigated region, followed by the Midlands, North Coast and South Coast regions. The regional differences in SFR are attributed to variations in the evapotranspiration rate and the climate in the homogenous regions.

In conclusion, soil and water conservation structures cause decreases in the stream flow across all regions, soil types and practices. This is because soil and water conservation structures intercept runoff and increase the amount of water infiltration into the soil, thereby slowing down and reducing the amount of water running off. The soil and water conservation practices, on the other hand, intercept water drops and decrease the kinetic energy of rain drops, which, in turn, increases the time necessary for the infiltration, hence reducing the runoff. According to Jewitt *et al.* (2009), activities that have an impact of greater than or equal to 10% of the MAR should be considered for declaration as SFRAs. Therefore, the SFR caused by soil and water conservation structures is insignificant (i.e. < 5.5%) and does not necessitate their declaration as SFRAs, as contained in the National Water Act of South Africa. However, if the soil and water conservation structures were to be eliminated, the SFR would decrease and soil erosion would increase, which is undesirable, and it would contribute to unsustainable long-term crop production.

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