Neutrinos and Nucleosynthesis

The production of elements in the universe is a highly investigated topic. There is an ongoing search for possible production sites of elements heavier than ^{56}Fe. The core-collapse supernova is such a possible production site and is unique due to the expected influence of the neutrinos leaving the proto neutron star, which is the end product of the evolution of a massive star and remnant of a core collapse supernova. It is proven, that neutrino matter interactions can alter the nucleosynthesis outcome.
During the collapse and the birth of the proto neutron star the core is driven to high densities and temperatures due to the ongoing compression by the gravitational force. These high densities and temperatures enhance the neutrino production of all flavors. Via the charged-current matter interaction, electron neutrinos and antineutrinos are produced:

$$\nu_e + n \longleftrightarrow p + e^- \qquad \text{and} \qquad \bar{\nu}_e + p \longleftrightarrow n + e^+ \quad .$$

As the inverse reactions produce either protons or neutrons they influence the so called proton-to-nucleon ratio Y_e, which determines where neutrino nucleosynthesis can happen and which processes are most likely to produce heavier elements in the given surroundings.
Approximately 10^{58} neutrinos with an average neutrino energy of 10 MeV leave the proto neutron star, carrying away almost 99% of the gravitational binding energy. An outcome of this neutrino emission are the neutrino driven winds, which are low-mass outflows driven by neutrino matter interactions. Neutrinos leaving the proto neutron star can interact with the surrounding matter via multiple reaction types, depending on the flavor of the neutrino. There are charged-current interactions where an electron or positron occurs in the final state. Another possibility is the neutral-current interaction where you have neither an electron or positron, these interactions are mainly scattering interactions with $\nu_{\mu,\tau}$ or $\bar{\nu}_{\mu,\tau}$. Furthermore there exists the possibility of scattering incidents as well as neutrino induced spallations, which can also be assigned to charged- or neutral-current interactions depending on the particles taking part in the interaction.
As already mentioned, the proton-to-neutron ratio determines different scenarios, that can cause different kinds of nucleosynthesis. Simulations suggest, that the matter ejected during a supernova can be slightly neutron rich at the beginning but will turn proton rich later. This indicated, that the rapid neutron capture (r-process) is not very likely to happen during a core-collapse supernova. Possible processes are the νp-process, the weak r-process and the ν-process. The νp-process occurs in the neutrino driven winds after the α-rich freeze out of the matter. This α-rich freeze out happens when the shock from the supernova explosion reaches the silicon rich shell and it means the break down of the matter into nuclei and α-particles. The nuclei produced during this freeze out act as seed for the νp-process. Here the antineutrino absorption on free protons produces neutrons. Via (n,p) and (p,γ) reactions there is a matter flow to heavier nuclei observable. The efficiency of this process is highly dependent on the proton-to-neutron ratio as well as the antineutrino luminosity.
If the matter in the neutrino driven winds is slightly neutron rich it is also possible for the weak r-process to happen. This process produces neutron rich nuclei up to mass number A$\sim$90. Nevertheless it is quite unsure if this process happens, as the supernova ejecta is most likely just slightly neutron rich in the earlier times of the explosion and a high neutron density is needed for this process to occur.
Another possible site of nucleosynthesis are the outer layers of the star, here the so called ν-process takes place and relies on the interaction of neutrinos with matter, either by charged-current interaction or neutral-current spallation leading to distinct abundance peaks for several nuclei, like ^{11}B or ^{7}Li.
As the nucleosynthesis outcome depends on the neutrinos involved in the interactions as well as on the energies of the neutrino flavors, there are very recent studies which suggest that neutrino oscillations could change the nucleosynthesis outcome. This is due to the fact, that these oscillations cause a swap in energy and luminosity spectra of the neutrinos. It is mainly important for reactions induced by electron neutrinos as the energy of electrons neutrinos is expected to be much smaller than of the other flavors. Therefore it is possible that these oscillations may have an impact on the nucleosynthesis in neutrino driven winds as well as the nucleosynthesis occuring in the outer supernova shells.